UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

HYDROLOGIC RECONNAISSANCE OF THE GEOTHERMAL AREA NEAR KLAMATH FALLS, OREGON

With a Section on

PRELIMINARY INTERPRETATION OF GEOPHYSICAL DATA

WATER-RESOURCES INVESTIGATION
OPEN-FILE REPORT WRI 76-127

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Donald L. Peterson

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Conversion of Units

and

List of Units

Multiply metric units	By	To obtain English units
	Length	
meters (m)	3.281	feet (ft)
kilometers (km)	.6214	miles (mi)
centimeters (cm)	.03281	feet (ft)
millimeters (mm)	.03937	inches (in)
	Area	
hectares (ha)	2.471	acres (a)
square kilometers (km^2)	.3861	square miles (mi^2)
	Volume	
cubic meters (m^3)	8.107×10^{-4}	acre feet (acre-ft)
cubic kilometers (km^3)	.2399	cubic miles (mi^3)
	Temperature	
degrees Celsius (^{o}C)	$(1.8 \times {^{o}C}) + 32$	degrees Fahrenheit (^{o}F)
	Flow	
liters per second ($l\ s^{-1}$)	15.85	gallons per minute ($gal\ min^{-1}$)
liters per second ($l\ s^{-1}$)	2.28×10^4	gallons per day ($gal\ day^{-1}$)
	Hydraulic Conductivity	
meters per day ($m\ day^{-1}$)	3.281	feet per day ($ft\ day^{-1}$)
	Transmissivity	
meters squared per day ($m^2\ day^{-1}$)	10.76	feet squared per day ($ft^2\ day^{-1}$)

Multiply metric units	by	To obtain English units

Specific Capacity

liters per second per meter ($l\ sec^{-1}\ m^{-1}$)	52.0	gallons per minute per foot ($gal\ min^{-1}\ ft^{-1}$)

Thermal Gradient

degrees Celsius per kilometer ($^oC\ km^{-1}$)	1.6	degrees Celsius per mile ($^oC\ mi^{-1}$)
degrees Celsius per kilometer ($^oC\ km^{-1}$)	.0305	degrees Celsius per 100 feet ($^oC/100\ ft$)

Thermal Conductivity

millicalories per centimeter per second per degree Celsius ($mcal\ cm^{-1}\ sec^{-1}\ {}^oC^{-1}$)

Heat Flow

microcalories per second per centimeter squared ($\mu cal\ sec^{-1}\ cm^{-2}$)

$$1\ \mu cal\ sec^{-1}\ cm^{-2} = 1\ \text{Heat Flow Unit (HFU)}$$

$$\text{HFU} = (\text{thermal conductivity}) \times (\text{thermal gradient}) \times 10^{-2}$$

$$= (mcal\ cm^{-1}\ sec^{-1}\ {}^oC^{-1}) \times ({}^oC\ km^{-1}) \times 10^{-2}$$

Specific Heat (Volumetric)

calories per centimeter cubed per degree Celsius ($cal\ cm^{-3}\ {}^oC^{-1}$)

HYDROLOGIC RECONNAISSANCE OF THE GEOTHERMAL AREA NEAR KLAMATH FALLS, OREGON

By E.A. Sammel

ABSTRACT

Geothermal phenomena observed in the vicinity of Klamath Falls include hot springs with temperatures that approach 204°F (96°C) (the approximate boiling temperature for the altitude), steam and water wells with temperatures that exceed 212°F (100°C), and hundreds of warm-water wells with temperatures mostly ranging from 68° to 95°F (20° to 35°C). Although warm waters are encountered by wells throughout much of the 350 square miles (900 square kilometers) of the area studied, waters with temperatures exceeding 140°F (60°C) are confined to three relatively restricted areas, the northeast part of the City of Klamath Falls, Olene Gap, and the southwest flank of the Klamath Hills.

The hot waters are located near, and are presumably related to, major fault and fracture zones of the Basin and Range type. The displaced crustal blocks are composed of basaltic flow rocks and pyroclastics of Miocene to Pleistocene age, and of sediments and basalt flows of the Yonna Formation of Pliocene age. Dip-slip movement along the high-angle faults may be as much as 6,000 feet (1,800 meters) at places.

Shallow ground water of local meteoric origin moves through the upper 1,000 to 1,500 feet (300 to 450 meters) of sediments and volcanic rocks at relatively slow rates. A small amount of ground water, perhaps 100,000 acre feet (1.2×10^8 cubic meters) per year, leaves the area in flow toward the southwest, but much of the ground water is discharged as evapotranspiration within the basin. Average annual precipitation on 7,317 square miles (18,951 square kilometers) of land surface near Klamath Falls is estimated to be 18.16 inches (461 millimeters), of which between 12 and 14 inches (305 and 356 millimeters) is estimated to be lost through evapotranspiration.

Within the older basaltic rocks of the area, hydraulic conductivities are greater than in the shallow sediments, and ground water may move relatively freely parallel to the northwest-southeast structural trend. Recharge to the geothermal systems probably occurs as water in the deeper basalt rocks, penetrating downward along the extensive fracture zones that transect the area.

Shallow meteoric water that is assumed to be the source of the thermal waters has low dissolved-solids concentrations generally dominated by calcium and bicarbonate. During its passage through the geothermal reservoir, the water gains dissolved solids in amounts up to about 900 milligrams per liter. Sodium and sulfate become the dominant ions. Chloride concentrations remain relatively low, and silica concentrations increase from an average of about 35 milligrams per liter to about 100 milligrams per liter.

Both cation ratios and silica concentrations in the hot waters indicate that reservoir temperatures are relatively low. The estimate arrived at in this study for the minimum reservoir temperature is 130°C. Silica concentrations are probably more reliable than cation ratios for estimates of reservoir temperatures for these waters. Other chemical indicators, including oxygen and deuterium isotopes, are consistent in indicating that reservoir temperatures are probably not much greater than the minimum estimate.

Temperature distributions and heat flows in the shallow rocks of the area are strongly influenced by convective flow of water. Most observed temperature gradients and estimated heat flows are believed to be unreliable as indicators of conditions in or directly above the thermal reservoir. Some evidence from temperature profiles suggests, however, that heat flow in the Lower Klamath Lake basin is about 1.4 microcalories per square centimeter per second (1.4 HFU), a value that is near the minimum expected for the Basin and Range province.

The net thermal flux discharged from springs and wells in the area is estimated to be on the order of 2×10^6 calories per second. Discharge by thermal waters into the shallow ground-water system beneath land surface may be many times this amount. Reportedly, at present only about 1,300 calories per second of geothermal heat is being put to beneficial use in the area.

A conceptual model of the geothermal system at Klamath Falls suggests that most of the observed phenomena result from transport of heat in a convective hot-water system closely related to the regional fault system. Temperatures at shallow depths are elevated above normal both by convective transport and by blockage of heat flow in sediments of low thermal conductivities. Circulation of meteoric water to depths of 10,000 to 14,000 feet (3,000 to 4,300 meters) could account for the temperatures that probably exist in the thermal reservoir, assuming temperature gradients of 30° to $40^{\circ}C$ per kilometer in a crustal zone of normal conductive heat flow. Circulation to shallower depths may be sufficient to warm the water to the required temperatures assuming the more likely conditions of convective transport of heat and the insulating effect of overlying sediments.

Heat contents in the shallow hot-water system (<3 kilometers depth) are probably in the range 12×10^{18} calories to 36×10^{18} calories. The geothermal resource at Klamath Falls may, therefore, be one of the largest in the United States.

INTRODUCTION

Objectives and scope of the study

The initial objectives of the study in the Klamath Falls area were to: (1) describe the hydrologic environment; (2) determine modes and quantities of recharge and discharge to the thermal and nonthermal reservoirs; (3) interpret geologic, geochemical, geophysical and hydrodynamic data in terms of the hydraulic and thermal characteristics of the geothermal reservoir; and (4) provide a basis for a detailed quantitative appraisal of the reservoir system. A fifth objective, that of developing and evaluating effective methods of reconnaissance, was fundamental in this as well as other geothermal studies then being carried on by the U.S. Geological Survey. Not all of these objectives were attained to the desired degree, particularly in their quantitative aspects, and it is clear that much remains to be accomplished in arriving at the fifth objective, that of developing effective reconnaissance methods.

The investigations reported here were made during the fall of 1973 and the first nine months of 1974. The area of intensive study covered approximately 350 square miles (mi^2) (900 square kilometers, km^2) of the Klamath River drainage basin (fig. 1), and included all major thermal anomalies in the immediate vicinity of Klamath Falls. Data were gathered in relatively uniform geographical distribution in order to obtain background information necessary for analysis of the thermal anomalies.

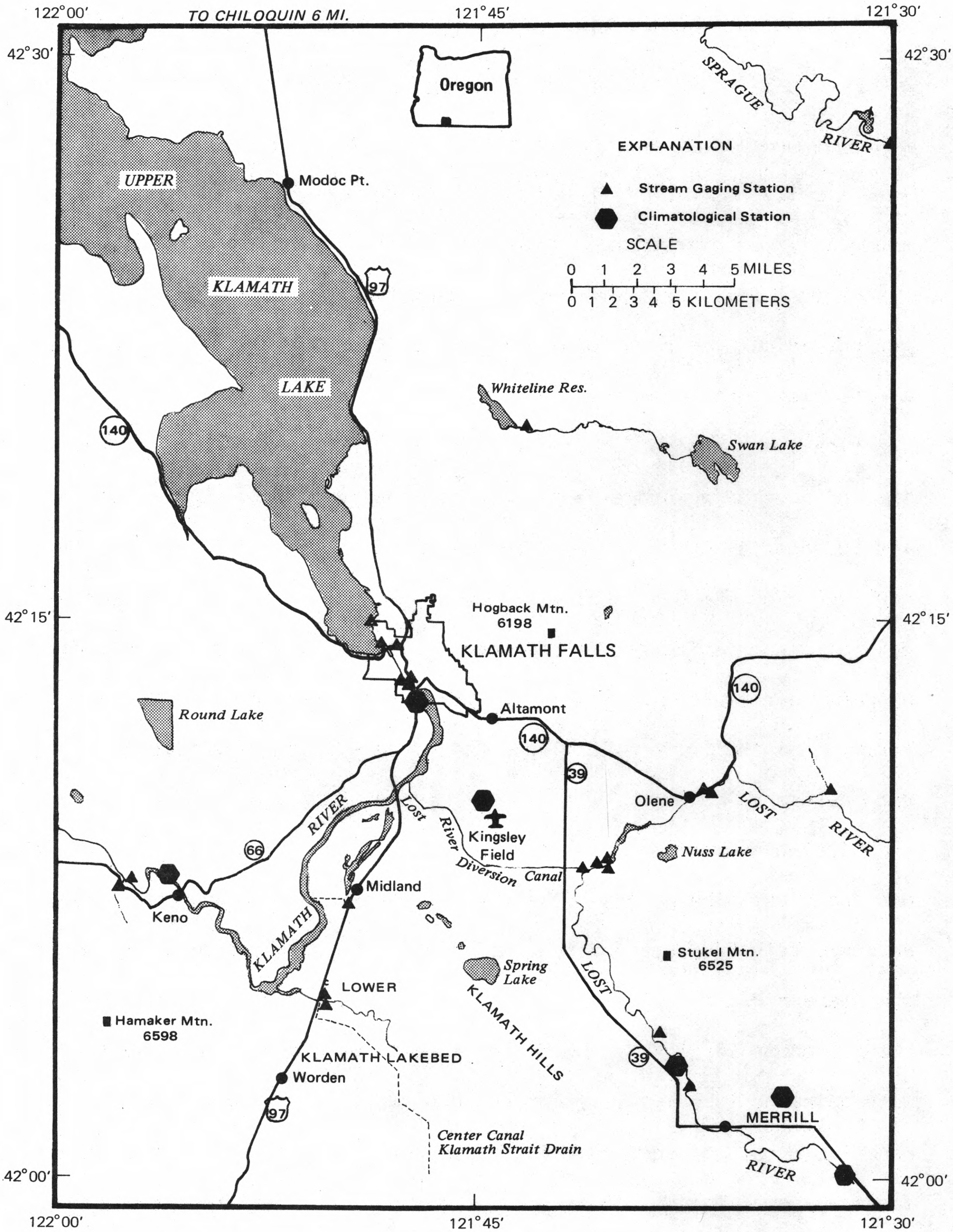

Figure 1 -- Index map of the Klamath Falls area, showing locations of U.S. Weather Bureau stations and stream gaging stations.

The so-called "hot-well area" of northeastern Klamath Falls was not included in this study. This area incorporates the most intensive and widely known manifestations of geothermal phenomena in the region, but, because of time limitations, an adequate study would have required the sacrifice of the overall view by a wider coverage of the geothermal areas. Furthermore, staff members of the Geo-Heat Utilization Center at Oregon Institute of Technology (OIT) had begun a study in this urban geothermal area, and this investigation is now supported by a grant under the geothermal research program of the U.S. Geological Survey.

Methods of Investigation

This report is based to a large extent on information obtained in an inventory of more than 300 wells and 20 springs in the Klamath Falls area. In most of these wells and springs measurements were made as appropriate of depth, water level, discharge, temperature, and specific electrical conductance. Driller's logs are available for about two-thirds of the wells.

Thirty-five samples of water were collected from wells and springs for chemical analysis. Carbonate bicarbonate, and pH were determined in the field and the remainder of the analyses were performed in Geological Survey laboratories. Relatively complete analyses of water from 22 additional sources were obtained from owners or from published data. Water was also collected from 32 wells and springs in the northern Klamath River basin for analysis of ^{18}O and deuterium isotopes.

A small amount of detailed geologic mapping was done, but in general the map by Peterson and McIntyre (1970) provided adequate detail for this reconnaissance.

Four shallow test holes were drilled by means of a power auger in the Lower Klamath Lake valley to depths ranging from 223 to 463 ft (68 to 141 m). Two 600-foot (183 m) holes were drilled for heat-flow information. Temperature profiles were obtained by means of a thermister probe in the six drill holes as well as in 41 unused water wells.

Additional geophysical data obtained during this investigation included gravity measurements at 103 stations in the Upper and Lower Klamath Lake basins and thermal infra-red imagery obtained in flights over about 300 mi^2 (780 km^2) of the area. The gravity measurements are discussed by Peterson in an appendix to this report. The infra-red imagery, however, has not been completely processed and is not discussed in this report. Preliminary visual examination of computer-generated contour plots based on the imagery suggests that properly calibrated high-resolution infra-red imagery may be useful as an exploration tool in areas of surficial convective thermal phenomena.

Acknowledgments

The authors wishes to acknowledge the assistance of many colleagues in the Geological Survey who provided services, advice, and inspiration. Aid received in the fields of water chemistry, isotope analysis, heat flow, and gravity investigations was particularly helpful. Gratitude is expressed to numerous other individuals and organizations who provided assistance and facilities during the study; in particular, the U.S. Bureau of Reclamation, Klamath Falls Project, for making facilities available and for help in ways too numerous to mention; to the U.S. Forest Service, Winema Forest Headquarters, for facilities and aid; to Jack Hitt and Professors John W. Lund, G.Gene Culver, Paul Lienau, and Larsen S. Svanevik, among others, at the Oregon Institute of Technology for facilities and aid during a study of wells at OIT; to Drs. James B. Koenig and Murray C. Gardner, GeothermEx Co., for making data available and for providing the first insights into the geothermal system at Klamath Falls; and to the hundreds of well owners who allowed us to visit, measure, and sample wells or, in some instances to drill test holes on their property. Finally, thanks are due to Nickolas E. Voegtly who cheerfully worked long hours through a cold winter to collect and compile data for this project.

Numbering System for Wells and Springs

In this report, wells and springs are numbered according to a system based on their location within townships, ranges, and sections referred to the Willamette Baseline and Meridian. Thus, the number 39/9-21 bcd1 specifies a well in Township 39 South, Range 9 East, and Section 21. The letters which follow indicate respectively the 1/4, 1/16, and 1/64 quadrants within the section according to the scheme illustrated in figure 2.

A number following the letters indicates that more than one well was inventoried in the same 1/64 section quadrant; such wells are numbered serially in chronological order of inventory. Each well number, therefore, specifies a location within a quadrant approximately 660 feet (201 m) on a side. Most wells shown on the accompanying maps are located with a probable error of less than 300 feet (91 m).

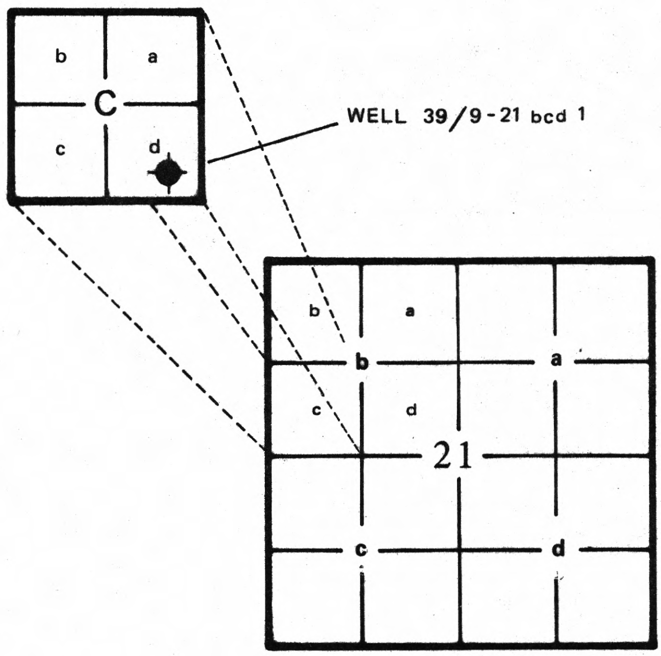

Figure 2.--Subdivision of Township and Range sections for well-numbering system.

REGIONAL SETTING

Regional Geology and Geothermal Activity

Klamath Falls is in the Basin and Range province near its western boundary with the Cascade range. Geologic structures in the area are typical of the Basin and Range province (Gilbert, 1928). Large grabens form the Upper and Lower Klamath Lake basins and these are flanked by uplifted blocks bounded by steeply dipping normal faults. The regional structure has a northwest-southeast alignment, but numerous faults have north-south strikes , and a few strike northeast-southwest.

Figure 3 shows geologic units and major faults in the Klamath area as mapped by Peterson and McIntyre (1970). The oldest rocks exposed in the area are of late Tertiary age; they include lacustrine and fluvial tuffaceous siltstone, sandstone, ashy diatomite, basaltic tuff and breccia, and a few thin basalt flows. These rocks were grouped by Newcomb (1958) in the Yonna Formation of Pliocene age. Later investigators have been reluctant to use this formation name because of uncertainties regarding the stratigraphic boundaries of the formation and the specific rock sequences that should be included. The name is used here solely for convenience.

Sediments of the Yonna Formation form the lower slopes of many upraised fault blocks in the area, and underlie most of the lacustrine and alluvial sediments in the structural basins. Ashy diatomites of the formation are conspicuous in road cuts and quarries in the area and are penetrated by many wells.

The most prevalent rocks of the Yonna Formation are thick, massively bedded, coarse-grained palagonitic sediments and pyroclastic rocks which are not clearly related to specific eruptive centers. Examples are rocks exposed in two of the large fault blocks south and east of Klamath Falls, Stukel and Hogback Mountains. Contemporaneous thin basaltic lavas are generally dense, black, glassy, and vesicular. Some, such as those exposed at the Klamath Rock Products quarry (T39, R8, Sec. 11), are brecciated and altered owing to extrusion into water or wet diatomaceous ooze (Peterson and McIntyre, 1970). These flows probably issued from nearby fissures which were subsequently covered. Such local volcanic activity is also indicated by a few scattered maar and tuff-ring deposits.

The massive diatomites of the Yonna Formation have counterparts in Butte Valley, California, about 20 mi (32 km) southwest of Klamath Falls, where they underlie Pliocene volcanic rocks of the High Cascades (Moore, 1937; Wood, 1960). Near Klamath Falls, diatomites are interbedded with Pliocene volcanic rocks (Meyer and Newcomb, 1952). The entire area over which these sediments are found may not have been covered by a continuous water body, but the lake or lakes must have been extensive.

Thickness of the Yonna Formation beneath the valley floors is largely unknown, but in adjacent ridges it ranges from a few feet (one meter) to at least 850 feet (260 m). The maximum thickness is inferred from the driller's log of a well at the Presbyterian Intercommunity Hospital, about one mile (1.6 km) north of Klamath Falls.

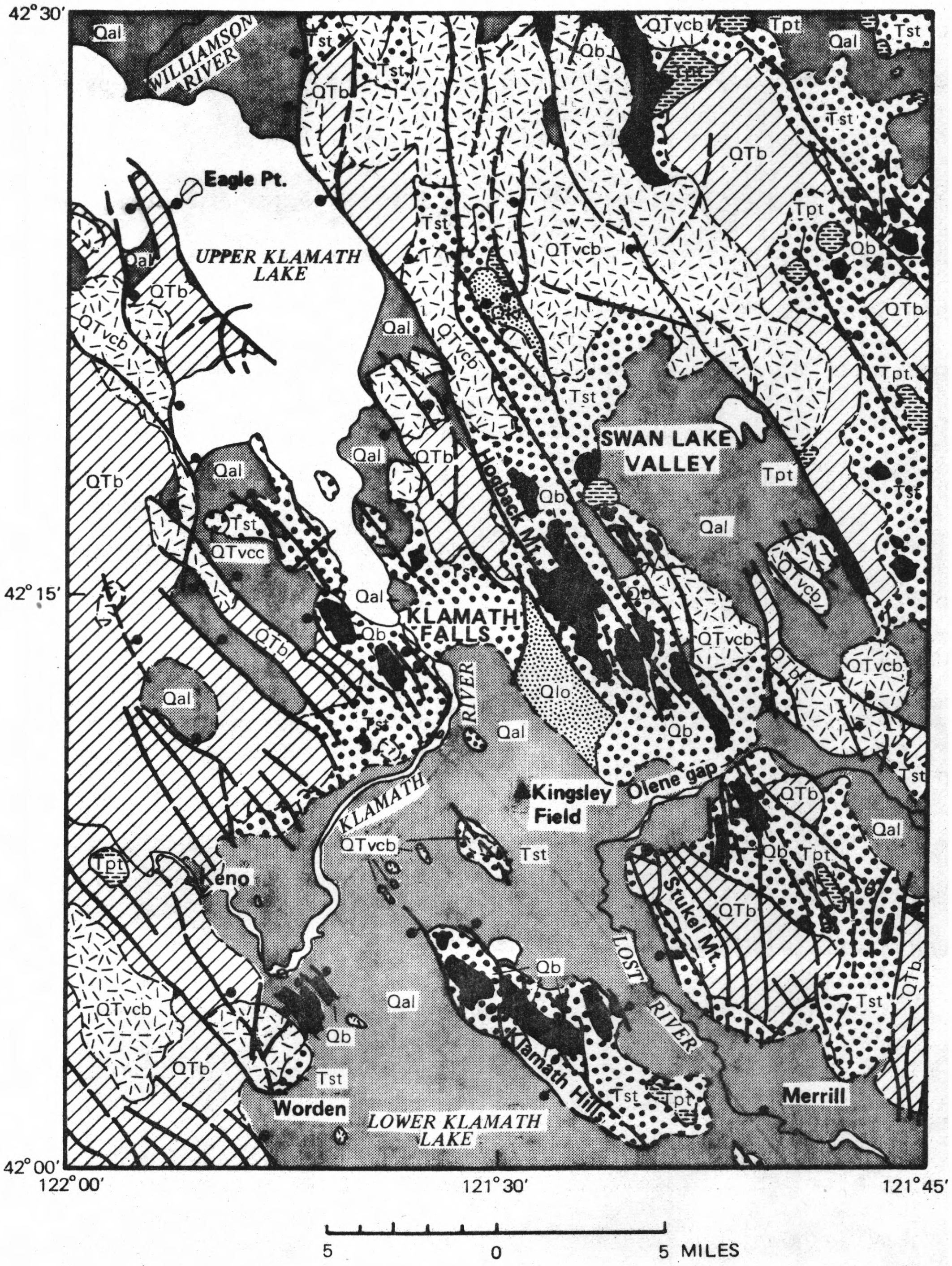

Figure 3. -- Geologic map of the Klamath Falls area

EXPLANATION

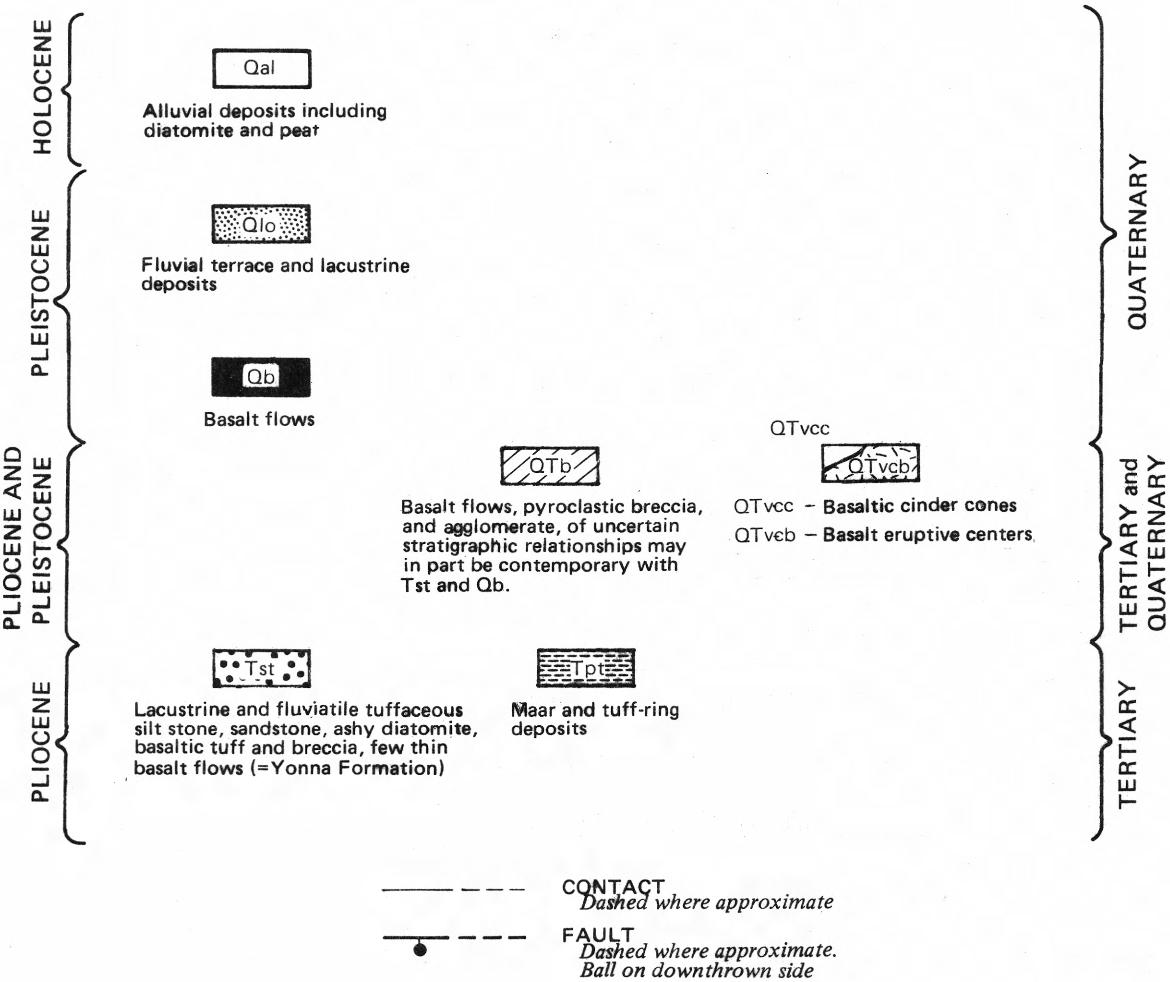

Figure 3. -- Continued

Rocks older than the Yonna Formation do not crop out in the vicinity of Klamath Falls, but the characteristics and probable ages of such rocks may be inferred from drillers' logs and from geologic mapping in adjacent areas. A few miles east of Klamath Falls in Swan Lake, Yonna, and Poe valleys, the Yonna Formation lies unconformably on olivine basalts of probable Pliocene age (Peterson and McIntyre, 1970; Leonard and Harris, 1974). The basalt is blue-gray to gray-brown, vesicular, and columnarly jointed. Individual flows are as much as 30 ft (10 m) thick and are interbedded with tuff and scoriaceous flow breccia (Leonard and Harris, 1974). Maximum observed thickness of the unit is about 300 ft (90 m) in the Yonna Valley. Similar rocks crop out in the Klamath River canyon southwest of Klamath Falls where their thickness is at least 820 ft (250 m) (Newcomb and Hart,1958).

The Olivine basalts described above probably correlate with extensive basaltic lavas south of Lower Klamath Lake in California (Wood, 1960). Flows there are similar to and probably contemporaneous with older basalts of the High Cascades mapped in adjacent Butte Valley, California (Wood, 1960), and in the Macdoel Quadrangle, California (Williams, 1949). According to Williams, the large shield volcanoes of the High Cascades which dominate the eastern margin of the Cascade Range were probably extruded from north-south trending fissures during a period extending from late Pliocene to Holocene time. The flows are composed largely of olivine-augite basalt, although andesite flows and related pyroclastic rocks are commonly interbedded. The major flows dip eastward and are buried by younger basalts and pyroclastic rocks in the hills immediately west of Klamath Falls.

Pliocene basalt flows underlie extensive areas of the Warner Range, about 80 mi (130 km) east of Klamath Falls. They mostly dip westward and probably underlie tuffs and lacustrine sediments of the Sprague River valley about 35 mi (60 km) northeast of Klamath Falls (Peterson and McIntyre, 1970). Thus, large volumes of basaltic lavas and pyroclastics were extruded onto relatively level surfaces in the region surrounding Klamath Falls during late Pliocene time. Similar flows probably also covered the Klamath Falls area. They are recorded in drillers' logs as massive gray to brown vesicular basalt and tuffaceous sediment underlying the Yonna Formation at places as the Oregon Institute of Technology, about 2 mi (3 km) north of Klamath Falls, at the Oregon Water Corporation wells in Klamath Falls, and possibly at a 1,300 ft (400 m) well on Hamaker Mountain south of Keno.

West of the High Cascade volcanoes, a belt of volcanic rocks from 30 to 40 mi (50 to 60 km) wide forms the Western Cascades. These rocks, consisting largely of pyroxene andesites, olivine basalts, and rhyolite tuffs and lava domes, were uplifted, folded, and deeply dissected prior to the High Cascade eruptions. Their ages range from Eocene to Pliocene (Williams, 1949), and are mostly equivalent to the Clarno Formation, John Day Formation, Columbia River Basalt Group and the Cedarville Series in the Warner Range of northeastern California.

The rocks of the Western Cascades are very thick. Along the Oregon-California border west of Klamath Falls the thickness is at least 12,000 ft (3,600 m) (Williams, 1949, p. 20). Although these rocks dip to the east beneath the High Cascades, they do not crop out in the vicinity of Klamath Falls and have not been penetrated by wells there.

Depth to and characteristics of pre-Tertiary rocks in the Klamath Falls area are unknown. The oldest rocks exposed in adjacent regions are metacherts and quartzites of probable Paleozoic age intruded by quartz monzonites of Jurassic age near the foot of Mount Shasta (Williams, 1949, p. 14). The Chico Formation (Cretaceous), consisting of arkosic sandstone, conglomerate, and shale, underlies parts of the Macdoel Quadrangle southwest of Klamath Falls (Williams, 1949), and it is possible that Cretaceous marine sedimentary rocks also underlie the Klamath Falls area, although no evidence of such rocks is known. Hot springs about 30 mi (50 km) southwest of Klamath Falls have high sodium chloride concentrations, however, which are attributed by Williams (1949, p. 55) to solution of chloride from the Chico Formation.

The structural development of the Klamath Falls area may have begun with normal faulting as early as Pliocene time (Peterson and McIntyre, 1970, p. 28). Subsequent to the deposition of the Yonna sediments and contemporaneous basalt flows, the entire region was apparently folded into broad anticlines and synclines with generally north-south axial trends. The Sycan Marsh-Bly-Beatty area was a broad syncline, and the Summer Lake-Goose Lake graben was an anticline. The Klamath Falls area may also have been an anticline whose crest subsequently dropped to form the present graben (Peterson and McIntyre, 1970, p. 29).

The volcanic activity and faulting that produced the present topography in the Klamath Falls area occurred mostly during the Pleistocene. To the west, new volcanic vents continued to form in the High Cascades,and stratovolcanoes such as Mts. Shasta, McLoughlin, and Mazama were built. The cataclysmic eruption of Mt. Mazama about 6,700 years ago resulted in thick deposits of ash and pumice that mantle the northern part of the area. Near Klamath Falls, widespread thin basalt flows were extruded over the Pliocene lacustrine sediments. Exposures of these vesicular, medium to dark gray, diktytaxitic Pleistocene basalts occur in the Klamath Hills, on Stukel Mountain south of Olene Gap, and on Hogback Mountain east of Klamath Falls.

Large volumes of Quaternary and Tertiary basalt flows and breccias of uncertain stratigraphic relationships underlie some of the highest ridges near Klamath Falls. These rocks may in part be contemporaneous with the Pliocene Yonna Formation, but in part are Pleistocene. Normal faults cut all of the above units as well as rocks of basalt eruptive centers which form some of the higher isolated hills.

The present-day basins of the Klamath Falls area were probably established early in the Pleistocene as the result of tensional fracturing of the entire region. Fluvial-terrace and lacustrine sediments were deposited in these basins at elevations as high as 200 ft (60 m) above the present valley floor, presumably as the result of high lake levels in late Pleistocene time. Some of these deposits are deformed by faults, indicating that deformation continued into late Pleistocene time (Peterson and McIntyre, 1970, p. 19). It is not certain, therefore, that the present levels of these deposits represent original altitudes of lake shorelines.

Basin and Range faulting in the Klamath Falls area reached a climax during Pelistocene time. Movement was almost entirely dip-slip along steeply-dipping (>60°) normal faults. The maximum amount of displacement is at least 980 ft (300 m) and may be as much as 6,000 ft (1,800 m) based on interpretations of gravity data. (See appendix to this report.) Some seismic activity has been reported in the region during historic times, but no historic surface breaks have been recorded (Couch and Lowell, 1971, p. 67).

Geothermal phenomena are widespread throughout the Klamath Falls area, but are confined principally to three locations: (1) an area of about 2 mi^2 (5 km^2) along the northeast edge of the city; (2) a stream-cut gap in the hills about 8 mi (13 km) southeast of the city at Olene Gap; and (3) the southwest flank of the Klamath Hills, about 12 mi (19 km) south of the city. These three areas are referred to in subsequent sections of the report as the "principal geothermal areas".

The geothermal manifestations include springs with temperatures that are generally less than the boiling point (less than approximately 204°F; 96°C), hot-water wells with subsurface temperatures that in a few places exceed the boiling point, and a few steam wells. Maximum temperatures are reported to be about 235°F (113°C) (Lund, and others, 1974). Hundreds of warm wells scattered throughout the area have water temperatures that range from just above normal for the region (60°F; 15°C) to about 104°F (40°C). Most of the wells with temperatures greater than 140°F (60°C) are confined to the Klamath Falls urban area. Wells and springs with temperatures greater than about 150°F (65°C) are located not farther than about a mile (1 ½ km) from the major fault zones. The association of the Klamath Falls geothermal phenomena with Basin and Range-type faults suggest an analogy with other geothermal areas of the Basin and Range province such as Warner Valley (Oregon), Surprise Valley (California), and a number of areas of Nevada.

Each of the principal geothermal areas of the Klamath Falls area displays abundant evidence of former hydrothermal activity in the form of silicified rocks. These rocks, such as the silicified palagonite tuff that crops out above the Presbyterian Intercommunity Hospital, occur at elevations up to several hundred feet (100 m) higher than any present surface flows of hot water. They indicate that the hydrothermal activity was formerly more extensive than at present and that either hydraulic heads in the hydrothermal system were much higher than at present or that the activity preceeded most of the displacement along the fault zones.

On the basis of data from several test holes in southeast Oregon, average conductive heat flow in this part of the Basin and Range province is probably about 1½ to 2 heat-flow units (HFU) (Sass and Sammel, 1976). This heat flow is very near the world wide average. In the area studied for this report, only two holes were drilled specifically for conductive heat-flow information. A number of temperature profiles obtained in unused wells, however, permits some additional estimates of conductive heat flow to be made. These data, discussed in a later section of this report, indicate that heat flow arriving within a few tens of feet (few meters) of land surface ranges from nearly zero, in several ground-water recharge zones, to about 3 HFU in volcanic sediments southeast of Klamath Falls. Higher heat flows may occur in the vicinity of the urban hot-well area of Klamath Falls, but measurements have not yet been made there.

The ultimate source of the high heat flow is not known. Peterson and Groh (1967, p. 229) imply the existence of a magma body at great depths; Peterson and McIntyre (1970, p. 37) point to the presence of dikes, intercalated sill-like masses, bleached and silicified rocks, deposits of calcite and gypsum, and a halo of mercury mineralization as suggesting the existence of a hot igneous mass at depth. An alternative explanation involving only deep circulation of meteoric water is discussed below under the heading "Conceptual Model of the Geothermal System."

Regional Hydrology

Precipitation

Local precipitation is the source of most ground water in the Klamath Falls area. Precipitation has been measured at 6 U.S. Weather Bureau stations in the vicinity of Klamath Falls (fig. 1) for periods ranging from 7 years for Rocky Point to 77 years for Klamath Falls (1973). Mean annual precipitaion at each of these stations is shown in table 1 for the period of record available.

Table 1.--Average annual precipitation and mean annual temperature measured at U.S. Weather Bureau stations in the vicinity of Klamath Falls.

Station	Elevation (ft/m above msl)	Period of Record used for this report	Mean Annual Precipitation (in/mm)	Mean Annual Temperature (°F/°C)
Chiloquin	4,198/1,279	1948-1973[a]	18.13/460	42.9/6.1
Keno	4,116/1,255	1948-1973[b]	19.49/495	--
Kingsley Field	4,085/1,245	1949-1973	11.93/303	46.6/8.1
Klamath Falls	4,098/1,249	1948-1973	14.37/365	48.0/8.9
Merrill	4,080/1,244	1953-1966[b]	11.80/300	--
Rocky Point	4,150/1,265	1967-1973[c]	23.15/588	44.6/7.0

a. Partial records for years 1964, 1968, and 1971 completed by estimates based on correlations with other stations.

b. Record for 1964 estimated by correlation with other stations.

c. Partial record for 1968 completed by internal correlation.

For three stations having periods of record longer than 26 years, Chiloquin, Keno, and Klamath Falls, long-term means are only slightly higher than those shown in table 1. The longer records show that the 1930's were a dry period and the 1950's were the wettest years of record. However, 1959, was the dryest year of record at all stations except Kingsley Field, which had a slightly drier year in 1949.

The range of annual precipitation at a given station is relatively great. Klamath Falls, for example, has a low of 7.31 in (186 mm) (1959) and a high of 20.91 in (531 mm) (1948). The range between stations is also great with a low of 11.80 in (300 mm) at Merrill and a high of 23.15 in (588 mm) at Rocky Point (table 1). Extremes in this part of the Klamath River Basin range from less than 10 in (254 mm) at Tulelake, California, to more than 60 in (1,524 mm) on the highest peaks north and west of Klamath Falls.

Local orographic effects largely determine the relative amounts of precipitation. Thus, of the moisture that reaches the area after passing over the Cascades on the westerly winds, most falls on the highlands and a relatively small amount reaches the valley floors.

In most years, between 60 and 70 percent of the total moisture falls during the months October through March. Most of this moisture is in the form of snow, although mid-winter rains are frequent in the valleys.

Estimates of average annual precipitation for the upper Klamath River Basin have been made based on rainfall maps published by the Oregon State Water Resources Board (1971). For the drainage basin above Klamath Falls, including sub-basins of the Williamson River, Sprague River, and Upper Klamath Lake, average annual precipitation was calculated to be 22 in (560 mm) over 3,820 mi^2 (9,895 km^2). For the basin below Klamath Falls, which includes the Lost River sub-basin of Oregon and California, areas were determined from U.S. Geological Survey topographic maps (Alturas and Weed sheets, scale 1:250,000), and isohyetals were transferred from Plates 2 and 2A of the Oregon State Water Resources Board publication. Precipitation was calculated to be about 15 in (380 mm) over 3,497 mi^2 (9,057 km^2). This estimate does not include the Meiss Lake closed basin, southwest of Dorris, California. On the basis of the above calculations, the average annual precipitation in the four sub-basins near Klamath Falls is 18.6 in (472 mm) over 7,317 mi^2 (18,950 km^2).

Temperature

Mean annual air temperature at stations near Klamath Falls ranges from 42.9°F (6.1°C) at Chiloquin to 48.0°F (8.9°C) at Klamath Falls (table 1). Elevations of stations reporting air temperatures range from 4,080 ft (1,244 m) at Merrill to 4,198 ft (1,279 m) at Chiloquin. At higher elevations, mean annual temperatures are considerably lower than those measured at the weather stations. No estimate of an average annual air temperature for this part of the basin has been made.

Temperatures of ground water in shallow aquifers near Klamath Falls range from about 44°F (7°C) to about 60°F (15°C) in those areas unaffected by thermal waters. Temperatures at individual sites may vary 10°F (5°C) or more annually. The average ground-water temperatures at most places in the area are probably several degrees higher than mean annual air temperatures.

Surface Water

Most of the surface water in the vicinity of Klamath Falls is derived from three streams: Sprague River, Williamson River, and Wood River. Williamson and Wood Rivers flow into Upper Klamath Lake and the Sprague River is a tributary to the Williamson. A significant amount of water also enters Upper Klamath Lake from springs and seeps in or near the lake and from small tributaries on its periphery. The average annual flow from all the above sources for the period 1930-1968 is estimated to be about 1,400,000 acre-ft (1.7×10^9 cubic meters, m^3) (Oregon State Water Resources Board, 1971, table 21).

Upper Klamath Lake, the largest natural lake in Oregon, has a surface area that varies between 98 and 140 mi^2 (254 and 362 km^2), depending on the lake stage, and a length of about 22 mi (35 km). Agency Lake, about 6 ½ mi (10 ½ km) in length, is appended to the northern end of Upper Klamath Lake. The average depth of Upper Klamath Lake is only 8 ft (2.4 m), although depths reach 40 to 50 ft (12 to 15 m) in a narrow trench between Eagle Ridge and Bare Island (Hubbard, 1970). Because of its shallow depth, regulated outflow, and generally warm waters, Upper Klamath Lake is undergoing relatively rapid eutrophication.

Water from Upper Klamath Lake flows through a narrow strait on the western edge of the city of Klamath Falls, meanders through marshlands toward the southwest, and then, after passing over a dam near the town of Keno, leaves the area through a narrow gorge cut into bedrock. Below Klamath Falls, the stream becomes the Klamath River.

More than 300,000 acre-ft (3.7×10^8 m^3) of water is diverted annually from Upper Klamath Lake and the Klamath River above Keno. This water is taken through three canals, the "A", the North, and the Ady, for use in irrigation in the Lower Klamath Lake basin. These canals are part of a major drainage and irrigation scheme built, and for the most part, operated by the U.S. Bureau of Reclamation (USBR). The project was begun in 1904, and is one of the oldest USBR projects in existence.

On the east side of the Lower Klamath Lake valley, Lost River enters through a narrow gap in the bordering hills and flows south into California. This stream has also been incorporated into the USBR project, and its flow is now totally regulated. From a diversion dam north of Stukel Mountain, water is either diverted to the Klamath River or is returned to the Lost River channel for use downstream. About 116,000 acre-ft (1.4×10^8 m^3) of water is annually distributed in the lower valley in this manner.

The network of canals and laterals which now serve the USBR Klamath Project totals about 700 mi (1,120 km) in length and irrigates about 200,000 acres (80,900 hectares , ha) of land in Oregon and California. Water in these canals flows generally south to the lowest part of the valley in the vicinity of Tulelake, California. Here, tailwater and ground-water seepage collect in a closed basin, which serves as a major wildlife refuge. The extent of the water surface in this swamp area is closely regulated, and excess water is pumped back to the north through the Klamath Straits Drain into the Klamath River. About 108,000 acre-ft (1.3×10^8 m^3) is annually pumped out of the lower valley in addition to an average net of 141,000 acre-ft (1.8×10^8 m^3) diverted to the Klamath River from Lost River through the Lost River Diversion Channel.

The above description of the USBR Klamath Project is an oversimplification of an extremely complex system. The average figures for inflow and outflow mean little in attempts to evaluate the hydrology of the Lower Klamath Lake valley. Only the major canals and drains are gaged, and the patterns of irrigation use and drainage are not readily available for quantitative evaluation. In the absence of detailed data, only the crudest generalizations are possible regarding Consumptive use, evapotranspiration, or recharge to the ground-water reservoir.

Since 1909 when the Southern Pacific Railroad dike was completed along the west side of the lower lake valley, separating the valley from the Klamath River, the Lower Klamath Lake in Oregon and California has been essentially a closed basin. It is likely, in fact, that the Tulelake area acted as a sump for some thousands of years previously. At present, water leaves the lower sump area only by evapotranspiration or by pumping which raises it approximately 15 ft (4.6 m) to its discharge point in the Klamath River.

The Klamath River, which now carries drainage from Upper and Lower Lake, Lost River, and the Tulelake sump, leaves the area west of Keno through a gorge which acts as a natural dam for both surface water and ground water. Average annual flow in the Klamath River at Keno is about 1,200,000 acre-ft (1.5×10^9 m^3). Ground-water underflow through the rocks of the river gorge below Keno is probably no more than 100,000 acre-ft (1.2×10^8 m^3) per year, and it is likely, therefore, that the Klamath River carries nearly all the water that flows from the basin.

Evapotranspiration

Rates of evapotranspiration in the upper Klamath River basin are not high, largely because of the relatively cool prevailing temperatures and the low rainfall. In the high dry valleys of the eastern part of the basin, evapotranspiration from sage and prairie vegetation may be less than 1 ft (0.3 m) per year (virtually the total precipitation). Estimates of evapotranspiration from the widespread marshes in the upper basin range from 3.6 ft (1.1 m) per year on 36,000 acres (14,600 ha) (Oregon State Water Resources Board, 1971, p. 104) to about 3 ft (0.9 m) per year on about 64,000 acres (25,900 ha) (Leonard and Harris, 1974). Evaporation from Upper Klamath Lake has been estimated at 3 ½ to 4 ft (1.1 to 1.2 m) per year, while estimates for Clear Lake (elevation 4,470 ft; 1,362 m) range from 2 ½ to 3½ ft (0.8 to 1.1 m) per year (Oregon State Water Resources Board, 1971, p. 50). Crop lands watered by surface irrigation total about 270,000 acres (1.1×10^5 ha) and consumptive use of water on these lands is estimated to be about 1.3 ft (0.4 m) per acre. Other crop lands supporting mostly grass and wheat and watered naturally by "sub-irrigation" total about 110,000 acres (44,500 ha). Consumptive use on these lands is estimated to be 1.3 ft (0.4 m) per acre (Oregon State Water Resources Board, 1971, p. 95).

Estimates of evapotranspiration for the upper Klamath River basin have been made by combining the calculated precipitation figures (see previous section) with streamflow figures from the U.S. Geological Survey. For 3,820 mi^2 (9,895 km^2) of the basin included in the

Williamson, Sprague, and Upper Klamath Lake sub-basins, precipitation has been estimated to be 22 in (560 mm) per year. Streamflow leaving the area is about 1,420,000 acre-ft (1.8×10^9 m^3) per year (including diversions to the "A" canal). The total of evapotranspiration and ground-water outflow is, therefore, calculated to be 3,096,000 acre-ft (3.8×10^9 m^3) per year. Illian (1970, p. 55) has estimated the amount of ground-water outflow from the Upper Klamath Lake and Sprague River sub-basins to be 350,000 acre-ft (4.3×10^8 m^3) per year. (See section on "Movement of Ground Water".) Accepting his estimate and subtracting 25,000 acre-ft (3.1×10^7 m^3) for flow into Upper Klamath Lake, evapotranspiration is calculated to be about 1.1 ft (0.34 m), per year for the three sub-basins. If ground-water outflow is assumed to be one-half the above estimate, the estimated evapotranspiration is 1.2 ft (0.37 m) per year.

For the 3,497 mi^2 (9,057 km^2) of the Lost River sub-basin in Oregon and California, precipitation is estimated to be about 15 in (380 mm). Streamflow has been estimated, on the basis of records at Keno and the Boyle Power Plant downstream, to be 1,280,000 acre-ft (1.6×10^9 m^3) at the Lost River basin boundary. Again introducing Illian's estimate of ground-water flow from the upper area into the Lost River sub-basin, the total of ground-water flow and evapotranspiration from the Lost River sub-basin is calculated to be 3,030,000 acre-ft (3.7×10^9 m^3) per year. On the basis of few data and largely by analogy with conditions assumed for Illian's estimate of ground-water flow, the amount of ground water leaving the basin below Keno has been estimated to be no more than 100,000 acre-ft (1.2×10^8 m^3) per year. (See section on "Ground Water Movement.") Subtracting this figure from the total losses arrived at above, evapotranspiration is calculated to be 1.3 ft (0.4 m) for the Lost River sub-basin.

RESULTS OF INVESTIGATIONS

Occurrence and Movement of Ground Water

The Shallow Reservoir

The ground-water reservoir in the sediments of the Upper and Lower Klamath Lake valleys is, for the most part, a continuous unconfined body to depths of more than 1,500 ft (460 m). Water levels range from land surface to 10 or 15 ft (3 or 4 m) below land surface, and annual fluctuations of the water table are generally less than 10 ft (3 m). Although few data are available in the highland areas, the shallow ground-water reservoir beneath the upraised rock masses appears also to be largely unconfined. Water levels in terrace sediments and alluvial fans are commonly 15 to 20 ft (5 to 6 m) below land surface, whereas at places under the higher bedrock ridges the water table is several hundred feet (100 m) below the surface. Fluctuations of the water table in the highlands are probably even smaller than those observed in the valleys.

Locations of wells and springs are shown on a map (fig. 4), data from the wells and springs are given in tables 2 and 3, and the generalized surface of the shallow ground-water reservoir is shown in figure 5. The water table is represented as a continuous, fairly smooth surface which forms a subdued replica of the topography. Examination of the water-level data for individual wells, however, discloses numerous departures from the smooth surface represented by the contour lines. As explained in the map text, some of these discrepancies result from errors of measurement or reporting. Many, however, represent real differences in water levels resulting from the local effects of geologic structure, stratigraphy, or permeability.

Compartmentalization of the shallow aquifer by faults undoubtedly occurs both in the valley sediments and the bedrock ridges. This compartmentalization may account for water-level discrepancies such as those on the southwest flank of the Klamath Hills and the edge of the hills near Keno. The effects are minor, however, throughout most of the volume of Pleistocene and Holocene sediments. Significant effects within the older sediments and volcanic rocks are discussed below in the section on "Deeper Basalt Aquifers."

Wells in the valley fill commonly show a decrease in static water level with depth; that is, the deeper wells have lower water levels. The lower levels are the result of partial confinement of the deeper zones of the aquifer and a loss of hydraulic head between the recharge areas and the zones tapped by the wells.

Hydraulic heads in wells are above land surface at several places in the area. Examples are wells north and east of Lake Ewauna (T38, R9, Sections 32 and 33), most wells north of Stukel Mountain (T39, R10, Sections 28-34), and some wells in Lost River valley south and west of Stukel Mountain. Many of these wells, particularly those north of Stukel Mountain, have large flows, but shut-in pressures indicate that artesian heads are low, generally less than 10 ft (3 m) above land surface. In the past years, hydraulic heads more than 20 ft (6 m) above land surface were reported in hot wells in the southeastern part of Klamath Falls, but in recent years the heads have declined to near land surface. The cause of the decline may be increasing use of water from hot wells in the Klamath Falls geothermal area.

Artesian heads in the area appear to be related to local confining conditions. Few artesian wells are more than a mile (1.6 km) from basin boundary faults, and it is assumed that the recharge areas for these wells are nearby. Examination of drillers' logs, where available, generally suggests that the water is confined in permeable zones between basalt flows, or in granular sediments overlain by clay and silt of the lake deposits.

A few shallow artesian wells in the flood plain of Lost River southeast of Klamath Falls (T39, R10, Sections 17-20) penetrate fine, black sand overlain by silt and clay. Well-drillers' logs and data from a Geological Survey test hole indicate that the sand may be hydraulically connected to recharge areas in Hogback Mountain through permeable deltaic or fan deposits which form a ridge extending southward from the mountain. The relatively high water levels in this ridge are apparent in figure 5.

Logs of wells in the area suggest that the zone of permeable sediments just described is also connected to the permeable terrace deposits on the north face of Stukel Mountain, as well as to subsurface stream gravels fanning out from Olene Gap. If so, the hot-water areas of Hogback Mountain, Stukel Mountain, and Olene Gap may be hydraulically connected through the valley sediments in a zone which extends to depths of 1,000 ft (300 m) or more.

Springs are not abundant in the Klamath Falls area, and most of these appear to have no connection with hotter water at depth. The seventeen springs shown in figure 4 comprise nearly all the identifiable perennial springs that issue at land surface. Springs issue from the bottom of Upper Klamath Lake, Spring Lake, Nuss Lake, and probably within other small ponds, but these have not been separately identified on the map.

Most springs in the area produce cold water supplied by gravity flow from precipitation on adjacent recharge areas. Examples are Hummingbird, Shell Rock, Barkeley, and Neubert Springs north of Klamath Falls, and an unnamed spring in the southwest part of the area (41/8-5cbb) all of which issue from basalts near the base of fault scarps. Eagle Point Spring and two springs in Olene Gap are warm artesian springs whose waters are partly derived from the geothermal reservoir. Thermal springs occur in Upper Klamath Lake but their temperatures are not known. Very hot springs formerly issued along the base of the slope below the hot-well area of Klamath Falls, but flows in these springs gradually diminished during the past 50 years and now have ceased at nearly all locations.

The general absence of springs on the flanks of the massive upraised fault blocks confirms other evidence that water tables are relatively deep beneath the surfaces of these blocks. Seeps occur following precipitation on the mountains, but as they are mostly short-lived the ground water is probably only temporarily perched above them.

Deeper Basalt Aquifers

A few wells penetrate basalt of probable Tertiary age in the ridges flanking the main valleys near Klamath Falls. Several of these wells produce hot water while other wells of similar depth produce cold water. The aquifers tapped by these two groups of wells appear to be hydraulically separated from the shallow aquifers of the basin.

Four of the deepest wells in the area have water levels that are discordant when compared with those in the local, shallow ground-water system. These are Oregon Institute of Technology (OIT) wells number 2, 5, and 6, and a recently drilled well at the Presbyterian Intercommunity Hospital. They produce hot water (140° - 192°F; 60° - 89°C) from strata that include rocks of both the Yonna Formation and older Tertiary basalt. Profiles of these wells and three cooler wells, OIT numbers 1,3, and 4, are shown in figure 6, along with inferred faults that cut the area. The deepest of the wells, OIT 6, is 1,805 ft (550 m) deep; it penetrates rocks that lie about 1,500 ft (460 m) below the level of Lower Klamath Lake. As the diagram illustrates, static water levels in the hot wells are accordant with each other but lie at depths ranging from 170 to 200 ft (52 to 61 m) below static levels in the three cooler wells and about 100 ft (30 m) below the average level of Upper Klamath Lake.

The explanation for this discordance among water levels in the OIT wells is not apparent. The hot wells have been shown by the results of an aquifer test to be hydraulically closely connected through permeable rocks. (See section on "Hydraulic Characteristics of the Rocks.") Thus, water levels in the hot wells probably represent the hydraulic potential

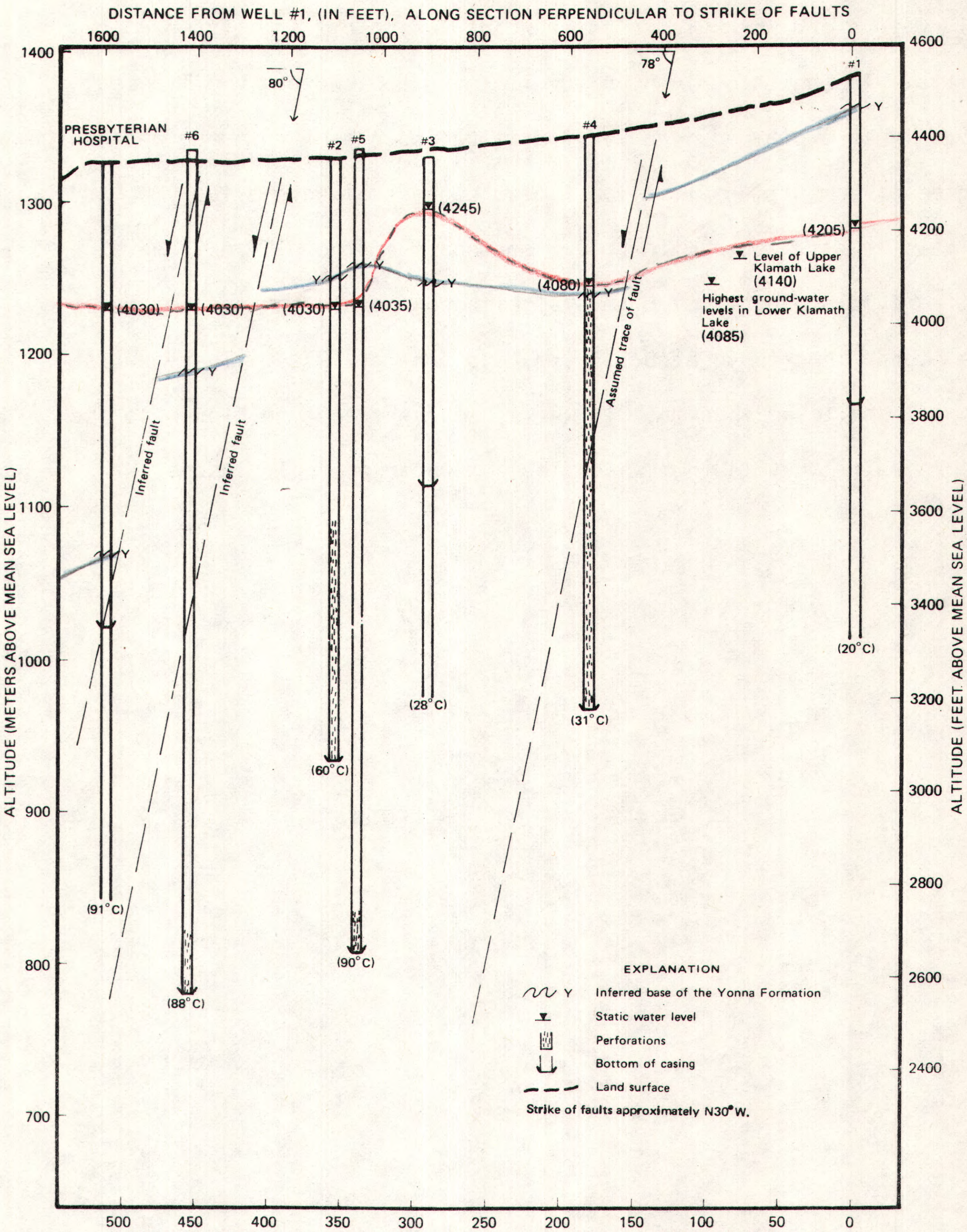

Figure 6. -- Profiles of Wells at Oregon Institute of Technology and Presbyterian Intercommunity Hospital, showing discordant water levels and assumed relations to faults.

in a regime whose origins are relatively far removed from the shallow cold waters and which is to some extent sealed off from the shallow waters. The anomalously high level of the cool water in OIT 3 most probably is explained by a very localized source of recharge and a high degree of compartmentalization in the bedrock at this site. Hot and cold wells situated a mile or two southeast of the OIT wells have similarly discordant water levels, although levels in most hot wells are higher than those at OIT (Lund, and others, 1974). These wells are all shallower than the OIT wells, however, and are closer to the major fault conduits from which the hot water probably issues.

One additional well that penetrates deeply buried basalt was inventoried in the Klamath Falls area. This is a 1,305-ft (398-m) well on the north flank of Hamaker Mountain (40/7-11ccc). The well produces water at a temperature of 61°F (16°C) from fractured basalt flows and fragmental interflow zones at depths of 1,260 to 1,288 ft (384 to 393 m) below land surface, corresponding to altitudes of about 3,600 to 3,572 ft (1,097 to 1,089 m) above sea level. Static water level in the well was reported by the driller in 1959 to be 1,193 ft (364 m) below land surface at an altitude of 3,670 ft (1,119 m) above sea level. The reported level is 400 ft (122 m) lower than water levels in shallow wells that penetrate bedrock at locations 2 or 3 mi (3 to 5 km) northeast in Keno.

The low static head in the Air Force well (at Hamaker Mountain) is probably related to compartmentalization of the aquifers by parallel faults that follow the regional trend through the area. A major fault has been mapped striking through Bear Valley, just northeast of the well (Murray Gardner, written comm., 1975). The fault is downthrown to the southwest, and numerous faults west of and parallel to the main fault also have downthrown blocks to the southwest. Thus, water levels may be stepped down to the southwest in partly independent compartments created by the faults.

The ground-water reservoirs in these fault blocks may be hydraulically connected to reservoirs in rocks of the Western Cascades which crop out to the west and may extend beneath the Klamath Falls area. Because the water level in the Air Force well is relatively high compared to average surface elevations in the Western Cascades, however, and because numerous faults transect the region, it seems unlikely that water in this well is derived from outcrop areas directly to the west. The well is more likely hydraulically connected to reservoirs to the northwest along the trend of the regional faults. In this direction, the Klamath River has cut its bed down to altitudes of only about 3,800 ft (1,160 m), thus allowing the possibility that connected basalt flows exist below this altitude. In the absence of deep-well data from the highlands west of Klamath Falls, however, these hypotheses are highly speculative.

Movement and Discharge of Ground Water

The water-level contours in figure 5 show that ground water in shallow aquifers near Klamath Falls moves southward toward the lower end of Lower Klamath Lake in California. Some of the flow, perhaps on the order of 80,000 acre-ft (9.9×10^7 m^3) per year, is intercepted by Lake Ewauna and the Klamath River, and leaves the basin as streamflow. Most of the flow moves southward at very slow rates, and, after satisfying evapotranspiration requirements along its path, the residual ground water enters the closed basins of Lower Klamath Lake and the Tulelake sump.

On the flanks of the northwest-southeast trending fault blocks, water-table gradients are steep, ranging from about 0.027 (140 ft mi^{-1}; 27 m km^{-1}) on the southwest side of Stukel Mountain to about 0.038 (200 ft mi^{-1}; 38 m km^{-1}) west of Lake Ewauna. These gradients reflect the steep surface topography and the influence of major faults. Vertical permeabilities within the fault blocks are apparently extremely low near the fault scarps, probably reflecting a high degree of anisotropy in the rocks caused by layering. The result is to impede the vertical component of flow through the fault blocks.

South of Altamont, the moderate gradient of about 0.0054 (29 ft mi^{-1}; 5.4 m km^{-1}) suggests that rather permeable sediments extend into the valley from the southern flank of Hogback Mountain. Lithologic descriptions in drillers' logs confirm this suggestion. Similar or even smaller gradients are observed along the northwest edge of the valley between Klamath Falls and Keno. These gradients indicate that ground water moves freely parallel to the regional structure.

Cold, meteoric water moves downward in places to recharge the ground-water reservoir. At other places, thermal waters move upward, discharging both water and heat to the near-surface environment. Temperature profiles obtained in unused wells indicate several areas where such vertical flow of ground water occurs. A pattern in figure 15 indicates those areas in which flow is predominantly upward. A second pattern indicates areas where movement of water is minimal and the flow of heat is dominantly conductive. In much of the remaining unpatterned area water probably moves downward to recharge the ground-water reservoir.

Temperature profiles also indicate places where highly stratified lateral flow of hot water occurs. One example is a region of several square miles at the southern edge of Klamath Falls in which warm water from the thermal area of the city flows southward in permeable zones of layered basalt. Similar flows undoubtedly exist elsewhere but are not well documented. The movement of thermal water is discussed further in the section on "Temperature Distribution and Heat Flow."

Large amounts of ground water probably move from one sub-basin to another within the Upper Klamath River basin. Illian (1970, p. 55) concludes that 200,000 acre-ft (2.5×10^8 m^3) per year enters the Lost River sub-basin from the Upper Klamath Lake sub-basin, and that 150,000 acre-ft (1.9×10^8 m^3) per year enters from the Sprague River sub-basin. According to Leonard and Harris (1974), however, the available data do not permit a quantitative evaluation of the interbasin movement, but suggest that a significant amount of flow occurs in the regional flow system.

A crude estimate of the amount of ground-water flow from the Upper Klamath Lake basin into Lower Klamath Lake may be made based on data provided by Illian and estimates derived from the present study. From data on wells in the Lower Basalt aquifer, Illian (1970, p. 13) found that the average specific capacity of the wells is 145 gallons per minute per foot of drawdown (2.8 liters per second per meter). A common method of estimating transmissivity is to multiply specific capacity in gallons per minute by 270 to obtain transmissivity in feet squared per day. The transmissivity estimated in this way is approximately 40,000 feet squared per day (ft^2 day^{-1}) (3,700 m^2 day^{-1}). Assuming that flow occurs through a 20-mi (32-km) cross section extending along the 4,100-ft (1,250-m) water level contour in figure 5, and that the average gradient is about 0.005, the volume of ground-water flow into the Lower Klamath Lake basin is calculated to be about 175,000 acre-ft (2.2×10^8 m^3) per year.

The estimated transmissivity is probably on the high side, as it is based largely on data from the highly permeable lower basalt aquifer in sub-basins north and east of Klamath Falls. A small amount of pumping test data suggests that the basalt aquifers are less permeable in the Klamath Falls area. The assumed gradient is probably within 25 percent of the actual value for the upper 1,000 to 1,500 ft (300 to 450 m) of the aquifer, but may be significantly higher than the actual gradients in a deep, regional flow system. As the assumed 20-mi (32-km) cross-section is a maximum length, the estimate of ground-water flow is near the probable upper limit of actual flow.

Although a similar approach to estimating ground-water flow out of the Lower Klamath Lake basin is possible, the uncertainties involved are much greater. It is assumed, first, that the regional ground-water flow should follow the regional topographic gradient toward the southwest. In this direction from Klamath Falls, however, ground-water conditions in the closely spaced parallel fault blocks are virtually unknown, and it is not possible to make realistic estimates of either transmissivities or gradients in this direction. The figure of 100,000 acre-ft (1.2×10^8 m^3) per year calculated above in the section on "Evapotranspiration" is, therefore, little more than a guess at a probable maximum ground-water flow from the basin.

Within the area studied for this report ground water is discharged at land surface by pumping from wells, by artesian flow from wells and springs, and by seepage to the land surface or into lakes and streams. No attempt has been made to estimate the total discharge into lakes and streams, but rough estimates of the remainder of the ground-water discharge have been made. The results are shown in table 4.

Table 4. --Summary of ground-water discharge and utilization in the Klamath Falls area.

	Gal $day^{-1} \times 10^6$ / liters sec^{-1}	Percent of Total
Public supply:		
Klamath Falls, Altamont, Merrill, and Falcon Heights	7.3/320	37
Irrigation	5.8/250	30
Industrial and commercial	3.0/130	15
Spring discharge	2.3/100	12
Space heating[1]	.9/ 40	5
Domestic (individual wells)	.2/ 10	1
Stock watering	.1/ 4	<1
Total	19.6/854	

[1] Interpreted in part from data in Lund and others, 1974.

The total discharge to the land surface of ground water from springs and wells in the Klamath Falls area is estimated to be about 2.0×10^7 gal day^{-1} (800 ℓ sec^{-1}), or about 22,000 acre-ft (2.7×10^7 m^3) per year. This amount is an extremely small percentage of the water available in the area either from streamflow or precipitation. (See section on "Regional Hydrology.")

Hydraulic Properties of the Rocks

Estimates from specific capacities of wells.--The specific capacities of wells afford crude estimates of the transmissivity of the aquifers penetrated by the wells. Specific capacity, expressed as yield in gallons per minute divided by the drawdown in feet, has been calculated from data provided by drillers and owners for about 170 wells in the Klamath Falls area. The results are shown in table 5.

Table 5.--Specific capacities of wells and estimates of transmissivity in aquifers of the Klamath Falls area.

Water-Yielding Rock Unit	Number of Wells	Average Depth (ft/m)	Specific Capacity (gal min^{-1} ft^{-1} / ℓ sec^{-1} m^{-1})	Estimated Transmissivity of Aquifer (ft^2 day^{-1} / m^2 day^{-1})
Alluvial terrace deposits	4	279/85	$1.8/3.5 \times 10^{-2}$	500/45
Holocene and Pleistocene lake deposits	24	194/59	$1.6/3.1 \times 10^{-2}$	400/35
Quaternary basalt	6	406/124	19/0.4	5,000/450
Quaternary and Tertiary basalt eruptive centers	27	187/57	$2.1/4.0 \times 10^{-2}$	600/55
Older lake deposits (Yonna Formation ?)	21	334/102	$1.9/3.6 \times 10^{-2}$	500/45
Yonna Formation	70	450/137	29/0.6	8,000/750
Quaternary and Tertiary basalt	18	869/265	37/0.7	10,000/930*

* Aquifer tests at two sites yielded values of about 20,000 and 11,000 ft^2 day^{-1} (1,860 and 1,022 m^2 day^{-1}, respectively) at prevailing temperatures.

Wells were assigned to one of several categories of rock types on the basis of the geologic map of Peterson and McIntyre (1970) and from drilling information. The assignment of many individual wells to a specific category of water-yielding rocks is questionable because of uncertainties in drillers' logs or in the mapping of the rocks, therefore, the units of table 5 are not necessarily the same as those of figure 3. Where the number of wells is small, reassignment of one high-yielding well would make a large difference in the average specific capacity for the rock unit. The general relations between groups, however, conform to estimates made from observations of outcrops.

The data of table 5 show that diverse rock types in the area provide similar yields to wells. Wells in alluvial terraces, Holocene and Pleistocene lake deposits, "older" lake deposits, and rocks of volcanic eruptive centers have specific capacities in the narrow range 1.6 to 2.1 gal min^{-1} ft^{-1} (3×10^{-2} to 4×10^{-2} ℓ sec^{-1} m^{-1}). These rocks, however, differ greatly in a fundamental hydraulic characteristic. Movement of water in the alluvial and lacustrine sediments occurs through intergranular pore space, whereas movement through the volcanic rocks and the "older" lake deposits occurs largely through fractures.

Drillers' logs do not clearly describe the "older" lake deposits, but they appear to be semi-consolidated to consolidated clay, silt, and diatomite, probably of the Yonna Formation. Most wells identified as penetrating the Yonna Formation have notably higher specific capacities than wells assigned to the "older" lake deposits. The higher yields result almost entirely from the presence of thin basalt flows and associated permeable volcanic rocks in the Yonna, particularly near its base. The presence of thin, interbedded basalt flows may represent the only significant difference between the Yonna rocks and those referred to as older lake deposits.

The distinction between the categories of "Quaternary basalt" and "Quaternary and Tertiary eruptive centers" in table 5 is arbitrary for many wells. Disagreements among published maps and uncertainties about stratigraphic relationships at depth preclude any confidence in these distinctions. However, the fragmental rocks of the eruptive centers of either Quaternary or Tertiary age appear to have similarly low permeabilities, whereas the basalt flows, regardless of age, are apparently much more permeable. As noted above, the permeable zones in the Yonna Formation are also associated with basalt flows.

Drillers' logs indicate that the moderately high permeabilities in the basalts of the Klamath Falls area are probably due largely to fractures rather than to permeable interflow zones such as occur elsewhere in many basalt sequences. Few of the drillers' logs describe the exact nature of the water-bearing zones,however, and it is possible that "caving" or "soft lava" rocks referred to by the drillers represent scoriacious or vesicular tops of flows which may also be relatively permeable.

Specific capacities listed in table 5 may be compared with two figures given by Illian (1970) for wells in the northern Klamath River basin. For wells in sedimentary aquifers, Illian (p. 11) reported an average specific capacity of 0.45 gal min^{-1} ft^{-1} (8.6×10^{-3} ℓ sec^{-1} m^{-1}), a value only about 1/4 as great as the corresponding value for the Klamath Falls area. For the "Lower Basalt Aquifer", Illian (p. 13) reports an average specific capacity of 145 gal min^{-1} ft^{-1} (2.8 ℓ sec^{-1} m^{-1}) a value almost 4 times greater than the corresponding figure in table 5. It is not known whether these discrepancies represent real differences between aquifers in the Klamath Falls area and those in the remainder of the northern Klamath River basin, or whether they merely reflect statistical discrepancies resulting from small sample populations and uncertain geologic classifications.

Transmissivity values in table 5 were calculated by simply multiplying the average values of specific capacity by 270 and rounding to the nearest hundred. It is not known whether this relation, based on rough estimates, is applicable to the anisotropic, fractured rocks of the Klamath Falls area, but the resulting transmissivity values are probably of the correct order of magnitude and on the conservative side.

Estimates from pumping tests in wells.--Analysis of data from two pumping tests in the Klamath Falls area has provided two independent estimates of transmissivity for the lower (Tertiary) basalt aquifer. The first test was conducted in 1956 by Robinson and Roberts, Groundwater Geologists, Tacoma, Washington, for the Weyerhauser Timber Company. The test was run in Weyerhauser well 4 (39/9-18cbb). The well is open in the lower basalt aquifer from 276 to 545 ft (84 to 166 m) below land surface. Analysis by the writer of data from this test suggests that transmissivity of the aquifer is about 11,000 ft^2 day^{-1} (1,020 m^2 day^{-1}). This value is close to the estimated average based on specific capacity of wells in older basalt (table 5).

An aquifer test was carried out in 1974 by the Geological Survey with the assistance of staff and maintenance personnel of the Oregon Institute of Technology. Well OIT 5 was pumped while observations of water levels were made in well OIT 6 and a well at Presbyterian Hospital (fig. 6). All these wells produce hot water (190° to 195°F; 88° to 91°C). The responses of the observation wells demonstrated conclusively that all three wells are hydraulically closely connected in a relatively permeable formation. The drawdown data provided a poor fit to curves based on standard analytical models, but the general shapes of the curves and the magnitudes of the drawdowns suggest that the apparent transmissivity is 22,000 ft^2 day^{-1} (2,045 m^2 day^{-1}). A correction factor of approximately 0.3 should be applied to this value in order to correct for the effects of high temperature on the viscosity and density of the water. Thus, the actual transmissivity may be less than 7,000 ft^2 day^{-1}

(715 m^2 day^{-1}) when the viscosity and density of cold water (assumed to be at 60°F; 16°C) is introduced into the calculations. Evidence of water levels as well as chemical data, presented later in this report, indicates that the Klamath Falls hot waters are nearly isolated from the local meteoric waters. The pumping test data suggest, however, that the isolated hot-water system has about the same transmissivity as the surrounding rocks.

QUALITY OF GROUND WATER

General Chemical Characteristics

Ground waters of the Klamath Falls area have relatively low hardness and dissolved-solids concentrations, and are generally of good quality for most uses. The thermal waters, as one might expect, have a higher dissolved-solids concentrations than meteoric waters. Concentrations in some of the warm waters are as high as 4,000 mg/l (milligrams per liter). Most waters, however, contain less than 700 mg/l of dissolved solids. The waters are generally mildly basic with pH's in the range 7.5 to 8.5.

Chemical analyses of water from 57 wells and springs in the vicinity of Klamath Falls are listed in table 6. Variations in the overall quality of ground water in the area are shown by contours on the values of specific conductance in figure 7. The nature of the individual waters is also indicated in figure 7 by Stiff diagrams. Finally, the dominant chemical characteristics of the ground waters are shown graphically by means of a diagram based on relative concentrations of cations and anions (fig.8).

In figure 8, the open circles represent the coldest and most dilute waters in the area. Most of these issue from basaltic rocks in springs such as Shell Rock, Neubert, Barkley, and Hummingbird Springs, located north of Klamath Falls, and Tulana Farms spring located 3 mi (4.8 km) southwest of Worden (41/8-5cbb). The dissolved solids are dominated by calcium, magnesium, and bicarbonate. Waters similar to those in the cold springs are found in a few deep wells penetrating basalt. One

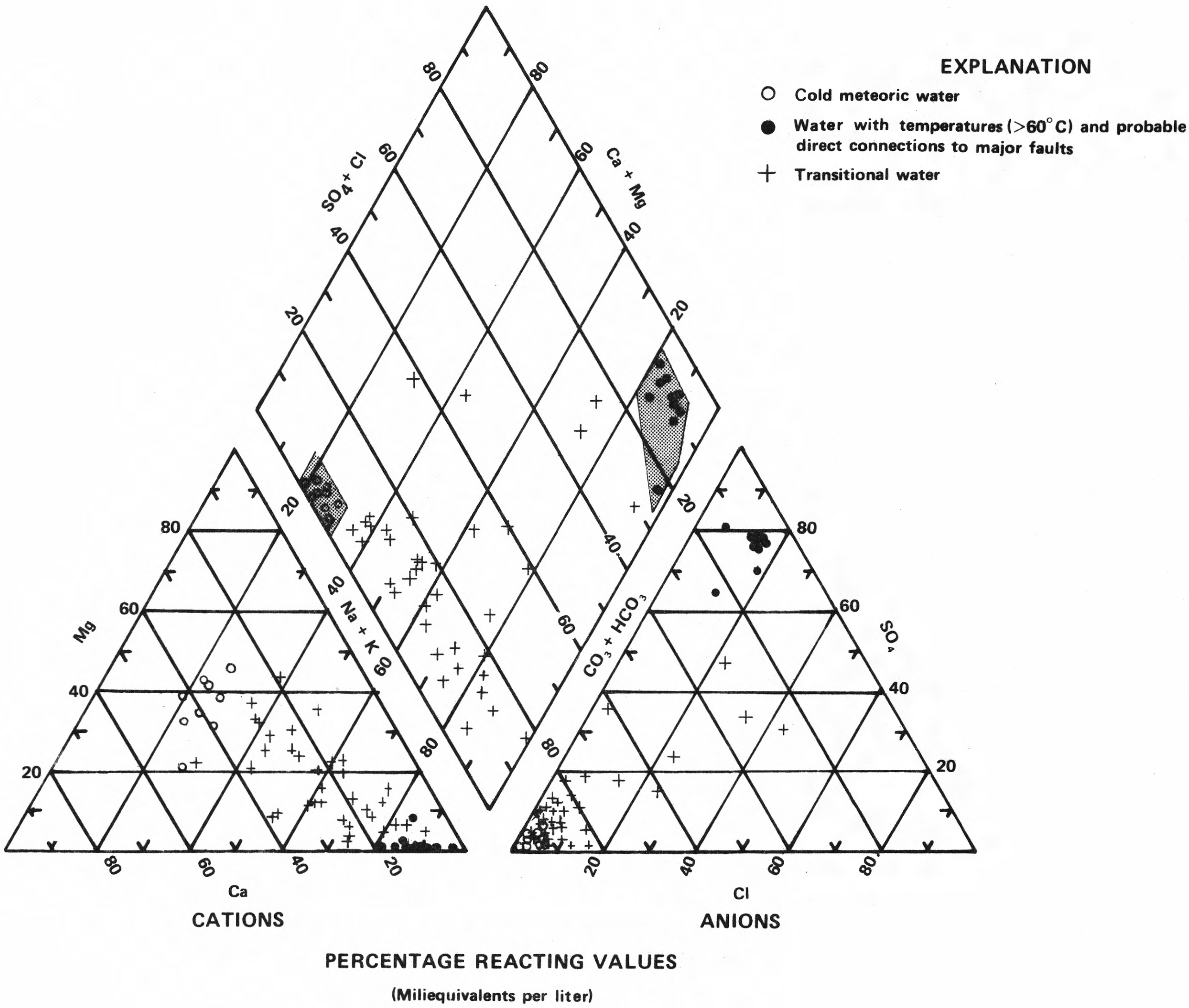

Figure 8. -- Relative abundances of major ions in ground water. Points on the cation and anion triangles are projected onto the diamond-shaped field along lines parallel to the outside 60° line of each triangle. The diamond-shaped field represents total cations plus total anions.

such well (40/7-11ccc), located northeast of Hamaker Mountain, is 1,305 ft (398 m) deep; another is a 700-ft (213-m) well (38/9-30acb) used for municipal supply in Klamath Falls. Waters of these springs and wells are believed to represent the dominant water type of the region, and their chemical characteristics have been used as a reference data in the chemical mixing models discussed below.

Waters of hot wells and springs (temperatures greater than 142°F; 61°C) are clearly distinguishable from other waters of the area by their high concentrations of sodium and sulfate and relatively low chloride concentrations (solid circles, fig. 8). This distinction appears to be valid for waters from each of the three major thermal areas--Klamath Falls, Olene Gap, and Klamath Hills. Most, if not all, of these waters are derived from basalts, and all are apprently associated with major faults. Dissolved-solids concentrations of these waters are relatively high (750-900 mg/l).

Examples of these thermal waters are found in wells at Oregon Institute of Technology (OIT 6), in Olene Gap Spring, and the Liskey and Osborn hot wells in the Klamath Hills. Preliminary results of an investigation by the Geo-Heat Utilization Center, Oregon Institute of Technology, show that the hot wells used for space heating in the northeast section of Klamath Falls also have waters of this composition. (John Lund, written commun., 1975). Temperatures in these wells are reported to be as high as 235°F (113°C). Hydrogen sulfide gas is detectable in many of these hot waters.

The remaining points in figure 8 represent warm waters (68° - 140°F; 20° - 60°C) which in part may be transitional between the two extremes. A few samples appear to be directly transitional, with sulfate increasing at the expense of bicarbonate. Most of the waters, however, follow a trend which results from an increase in sodium and a decrease in calcium, with bicarbonate remaining relatively abundant.

Warm waters occur at widely scattered locations throughout the valley areas in the Upper and Lower Klamath Lake basins. They are generally high in sodium and bicarbonate and have a wide range of dissolved-solids concentrations. Produced mostly from the Yonna Formation and from alluvial and lacustrine sediments, these waters appear to represent various mixtures of recent meteoric water with warm water of deeper circulation.

In much of the area south of Klamath Falls between Olene Gap and the Klamath River, ground water contains dissolved methane and excessive iron, and is not considered potable. Estimates based on specific conductances indicate that dissolved-solids concentrations are as high as several thousand milligrams per liter in water from this area. The chemical quality of this water may be explained in the following way. Drillers' logs from the area show that buried marsh deposits are prevalent in the lake sediments to depths of hundreds of feet. Furthermore, evidence from temperature profiles indicates that hot ground water from the Klamath Falls geothermal area flows southward into this area through permeable rocks which appear to dip beneath the sediments of the Lower Klamath Lake basin. The hot water cools as it mixes with shallow meteoric water in sediments of the lower basin, but it effectively extracts large amounts of dissolved solids from the sediments in its path. The area south of Klamath Falls seems, therefore, to have been a warm marshy sump during long periods of Pleistocene and Holocene time, and this history is reflected in the present chemical character of the water.

Silica Content

Measured silica concentrations in waters of the Klamath Falls area range from 24 mg/l to 118 mg/l (table 6). Many of the values in table 6 are from reported analyses, some of them more than 20 years old, and some of these values may be erroneous. It is known that the results of analyses of silica are particularly sensitive to the treatment of samples and methods of analysis. In many waters, part of the dissolved silica may polymerize after sampling and may not be detected by certain analytical methods. Depending on the method of analysis, therefore, it may be necessary to dilute the samples in order to avoid polymerization of silica. Six wells with suspected low silica values were resampled during this study, and silica concentrations were found to be as much as three times higher than the reported values. Waters from Barkley Springs, Weyerhauser #4, Jones Spring, Tulana Spring, and the Oregon Water Corporation wells were not reanalyzed and their silica concentrations in table 6 are probably too low.

The solubility of silica in water increases as temperature increases, and, therefore, the relation of silica concentrations to temperaure is used as a geothermometer for thermal reservoirs (Fournier and Rowe, 1966). As shown by figure 9, however, the relation of silica concentrations to measured temperatures in ground waters of the Klamath Falls area shows much scatter and a trend of extremely small slope. The group of wells (solid circles) on the left side of the diagram comprises the 10 hottest wells sampled. These data points form a generally linear trend in which silica concentrations are similar.

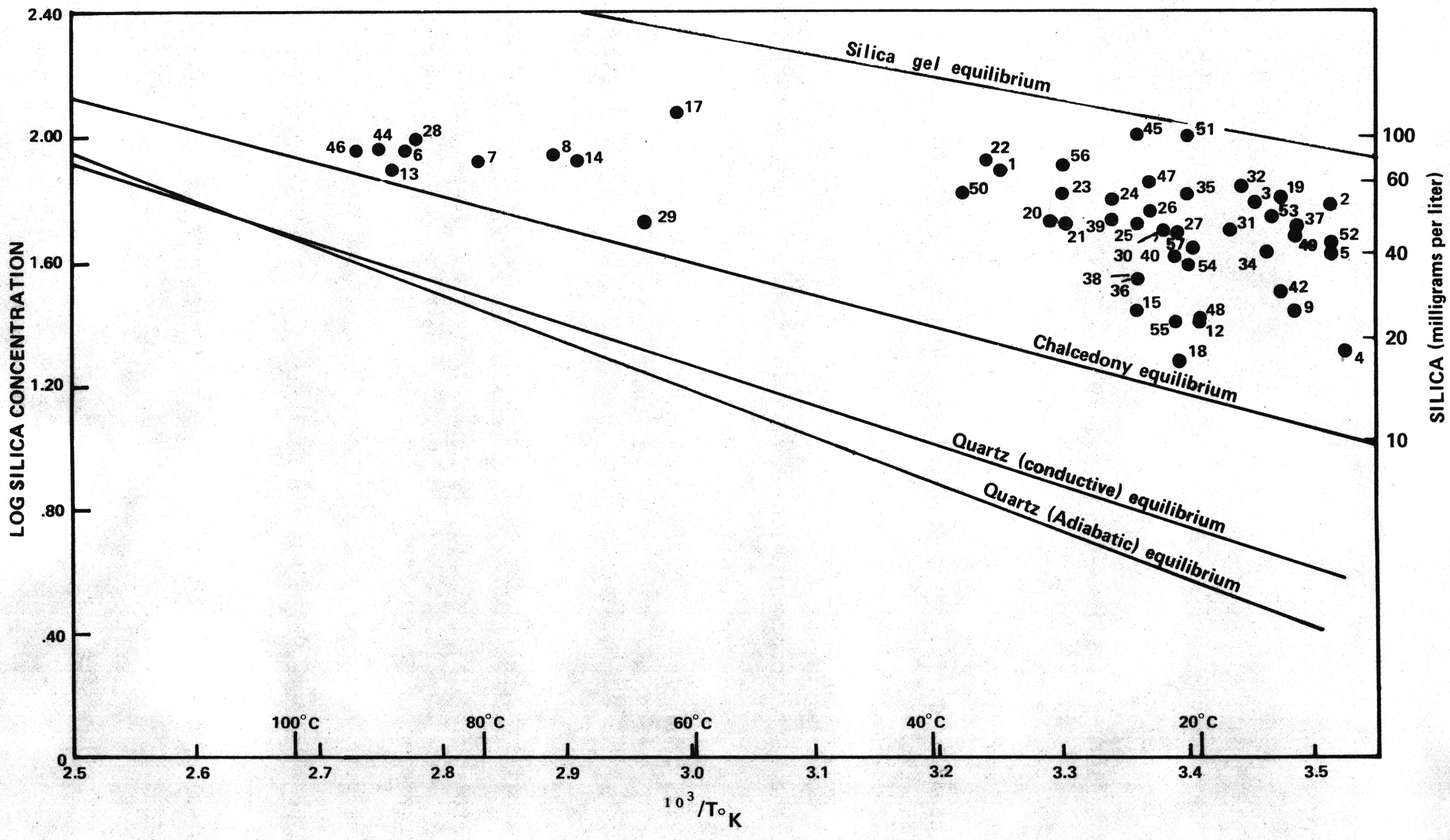

Figure 9. -- Measured temperature of ground water versus log silica concentration. Straight lines show empirical relations of temperature to equilibrium concentrations of quartz, chalcedony, and silica gel (Fournier, 1976).

The lack of samples with temperatures between 104° and 140°F (40° and 60°C) is fortuitous, although this gap in the data is probably related to the actual distribution of temperatures in waters of the area. Of the nearly 300 water temperatures measured in this study, only three fell in the range 104° to 140°F (40° to 60°C). It seems clear that the hottest waters are restricted to relatively small areas, and that outside these areas temperatures drop sharply. Moderate temperatures of 54° to 104°F (12° to 40°C) are, however, widespread throughout the area in what are assumed to be mixtures of thermal and meteoric waters. If additional wells were sampled in the areas immediately adjacent to the hot-water zones, a few temperatures in the range 104° to 140°F (40° to 60°C) would probably be encountered. If these are mixed waters as assumed, the silica concentrations should form a continuum with the hot and cold ends of the spectrum.

The range of silica concentrations decreases as water temperatures increases above 68°F (20°C). For example, in waters with temperatures between 68° and 77°F (20° and 25°C) silica concentrations range from 25 to 100 mg/l, whereas at temperatures between 149° and 199°F (65° and 93°C), concentrations range only from 75 to 98 mg/l. Although the number of samples is too small for statistical reliability, the narrow range of silica concentrations in hot waters suggests that waters from the several thermal zones have reached equilibrium with similar silicate phases at similar temperatures. This conclusion is supported by additional chemical evidence discussed in the succeeding section.

The high silica concentrations in waters of low temperature may result, in some instances, from solution of silica from deposits of diatomite or ash which are abundant in the Yonna Formation. Examination of drillers' logs reveals that at least 10 of the wells from which water samples were collected reportedly penetrate "chalk" rock, the local name for the ashy diatomite deposits. More than 20 additional wells appear to have penetrated significant thicknesses of the Yonna Formation, and, therefore, may have encountered similar deposits not reported by drillers. Attempts to relate silica concentrations to reported occurrences of chalk rock, however, failed to reveal any positive correlation. High silica concentrations were found in warm waters from wells which almost certainly did not penetrate diatomite, and low silica concentrations are found in wells yielding warm water which reportedly penetrate from 670 to 1,000 ft (204 to 304 m) of chalk rock (wells 36, 48, 54, and 55).

Several reasons may be advanced in explanation of the apparent lack of correlation between silica content in the ground water and the occurrence of diatomite deposits. First, most of what has been termed "chalk rock" by drillers is clearly not diatomite or ash, particularly in the thick sections that have been lumped under this term. Second, the shaly and chalky rocks of the Yonna Formation are extremely impermeable, and most of the water produced by wells that penetrate the Yonna Formation is derived from interbedded or underlying basalt. Temperature profiles and drillers' information indicate that vertical flow through the Yonna Formation is very small, and hence, there may be negligible contribution of silica-bearing water from overlying siliceous beds.

Relations Among Dissolved Constituents

Ratios of dissolved constitutents in waters of the Klamath Falls area show wide variations which depend on the source and history of the water. Relations between major constituents are presented in table 7 and are shown graphically in accompanying illustrations.

The ratios of dissolved constituents in table 7 show that the hot waters of the area have remarkably similar chemical compositions whether they are produced by springs at Olene Gap or by wells in Klamath Falls or the Klamath Hills. Compositions of warm and cold waters, however, are extremely diverse, and groupings of these waters according to area or temperature show little uniformity in chemical characteristics. Several warm waters of the Klamath Hills area have been listed separately in table 7 in an attempt to discover ratios of special significance in these waters. In the following sections, chemical symbols are used for convenience in expressing ratios.

Ratios of Na/K are rather high in the hot waters, suggesting by analogy with other geothermal reservoirs that these waters equilibrated at a temperature that was not greatly in excess of the measured water temperatures. (See Mariner and Willey, 1976; White, 1970, p. 68, 69). Furthermore, although there is some indication that the Na/K ratio unaccountably decreases as the thermal waters cool, the data for the warm wells are extremely erratic and the indications are probably not reliable. The Na/K ratio is at best a qualitative geothermometer and should not be relied upon at places where, as at Klamath Falls, the Ca/Na ratios are greater than one and indicated temperatures are low (Fournier and Truesdell, 1973, p. 1272).

Ca/Mg ratios are high in the hot waters and low in both cold and warm waters. High Ca/Mg ratios are generally characteristic of high-temperature systems, but may occur at temperatures as low as 100°C (White, 1970, p. 70). Ca concentrations, on the other hand, increase in the hot waters relative to the cold waters in general conformity with an increase in total dissolved solids.

Ratios of HCO_3/Ca are low in 9 of the 10 hot waters (0.9 to 1.6), but not as low as would be expected were the reservoir temperature extremely high (White, 1970, p. 69). The warm and cold waters of the area have similar moderately high ratios. Ratios of Cl/Ca are moderately high in the hot waters and low in the cold waters and most warm waters. Thus, the HCO_3/Ca and Ca/Mg ratios suggest that most warm waters appear to approach equilibrium with respect to Ca, Mg, and HCO_3 in short distances and times.

Wide ranges of both Cl and SO_4 concentrations occur, and although many of the calculated ratios of these elements are not reliable owing to their low concentrations, an increase in the SO_4/Cl ratios is indicated for the hot waters relative to the cold waters. The data also suggest that some warm waters of the Klamath Hills area may be distinguished from other waters by their low SO_4/Cl ratios at high Cl concentrations. If the hot waters are assumed to be derived from the cold, meteoric waters of the area, SO_4 is enriched as the waters are heated. This enrichment remains in many, although not all, of the warm waters.

The suggestion that warm waters of the Klamath Hills are distinct from other waters is further supported by the relations between water temperature and concentrations of Cl and SO_4 ions. As shown in the graph of figure 10, the hot waters have moderately high Cl contents and there is the suggestion of a dilution trend (line A) from the hot waters to the cluster of cold, meteoric waters. It seems clear, however, that the high Cl waters of the Klamath Hills have a separate dilution trend (line B). Several data points have been projected onto the trend lines, and it is suggested that waters represented by these and similar points have cooled while retaining the same Cl concentrations.

Relations similar to the one shown by the Cl-temperature graph are also demonstrated by a graph of SO_4 versus temperature (figure 11) and ratios of Cl/B, Cl/silica, and Cl/SO_4 (table 7). The Cl/B ratios show much scatter, partly because of uncertainties in the data for waters of very low Cl and B concentrations.

The significance of the relative and absolute amounts of Cl and B in the waters is not completely clear. The absence of a significant increase of B over Cl in the hot waters would seem to rule out the possibility of large concentrations of B to the hot waters by vapor transport from an underlying reservoir. Rather, small amounts of B may be lost from the hot waters as the result of minor boiling and vaporization as the waters ascend, although this effect is probably insignificant. Even though chloride concentrations in the Klamath Hills warm waters are not high compared to those in many hot-water systems (for examples, see White, 1970), the high relative amounts of Cl suggest a chemical development separate from other warm waters of the area.

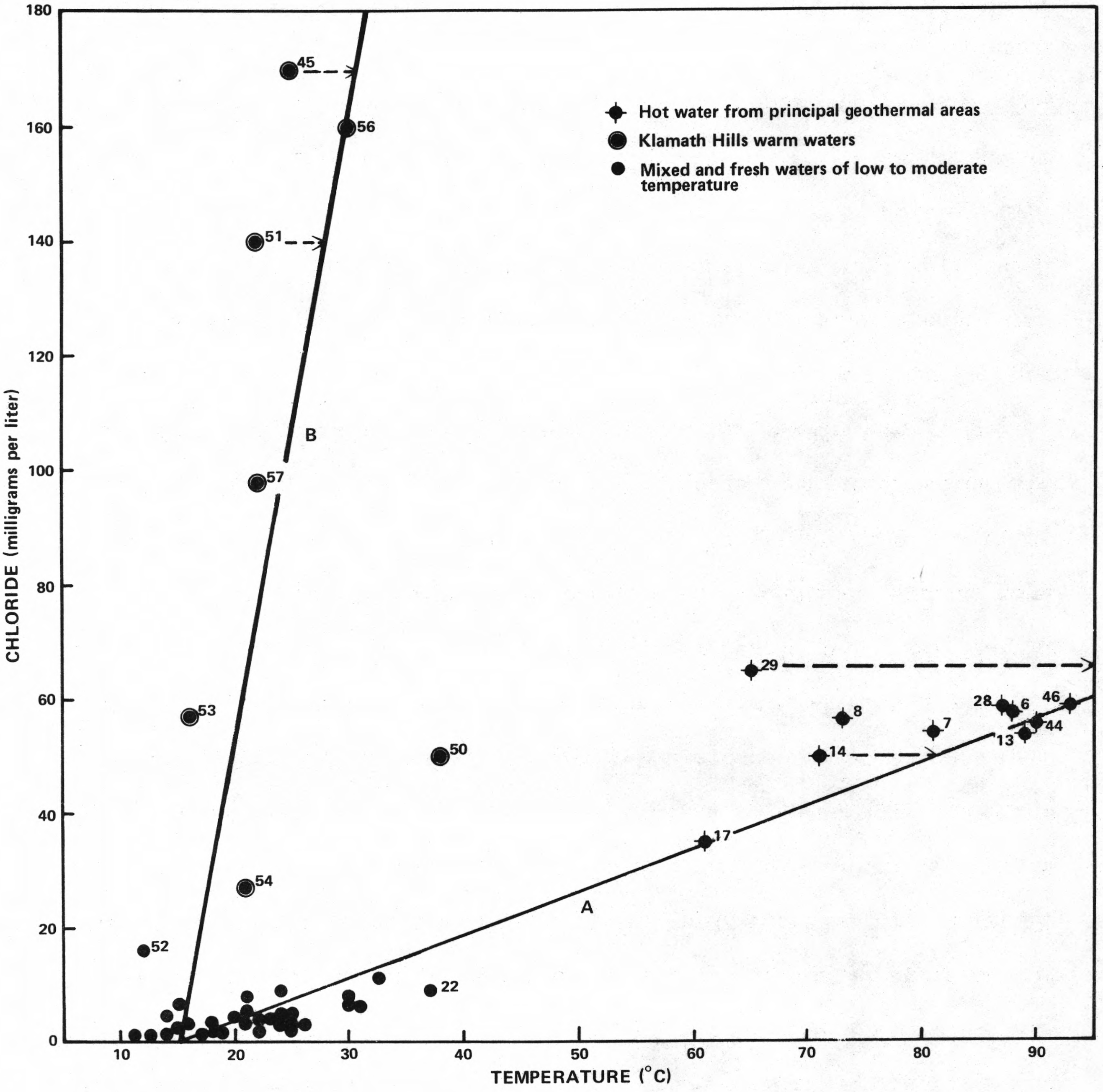

Figure 10. -- Temperature of ground water versus chloride concentration, showing two possible dilution trends (lines A and B).

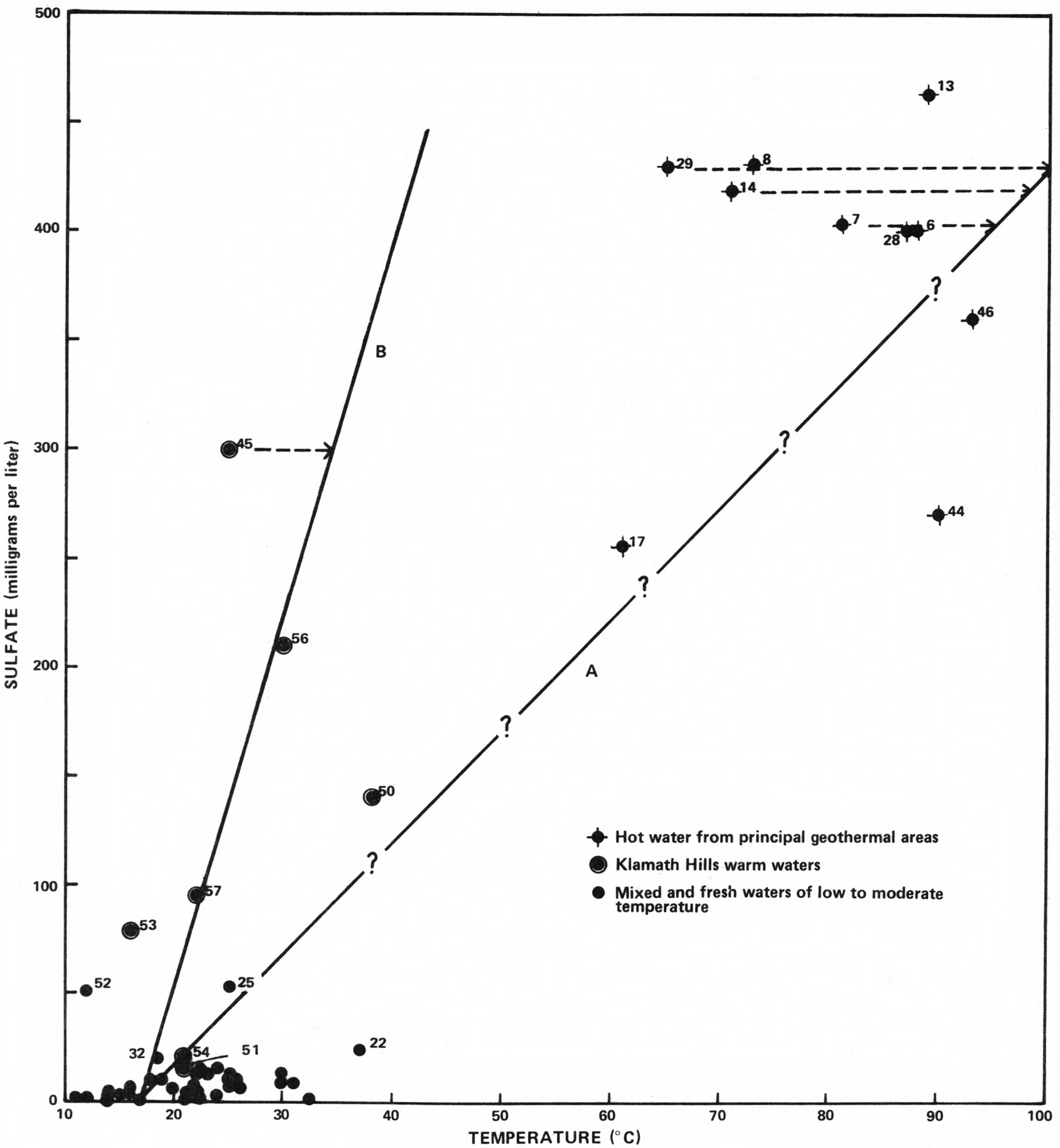

Figure 11. -- Temperature of ground water versus sulfate concentration, showing two possible dilution trends (lines A and B).

Most of the data included in figures 10 and 11 and table 7 tend to reinforce the concept of two separate groups of geothermal waters: (1) the hot waters of the three principal geothermal areas, and (2) warm waters of the Klamath Hills area. No waters clearly intermediate between these groups have been encountered. Dilution trends appear to be established by the data for each of the groups, although the trends are poorly defined for the hot waters. A few anomalous samples cannot be fitted into either group. Many of the ionic ratios in sample 13, for example, depart significantly from those of other hot waters, and among the Klamath Hills waters, samples 50 and 52 have characteristics that cannot easily be explained in terms of either the hot or warm waters. Explanations for these and others anomalies will require further study.

Low ratios of (HCO_3 + CO_3) to Cl clearly distinguish hot waters from other waters in the area, and confirm other evidence of the high degree of uniformity in the hot waters. Cold waters have uniformly high ratios, and warm waters generally have ratios that are close to those of the cold waters. Several of the Klamath Hills warm waters, however, have low ratios close to those of the hot waters. Temperatures in the hot waters range over more than 54°F (30°C) with no significant change in the (HCO_3 + CO_3)/Cl ratios, whereas in the cold waters, within an 18°F (10°C) temperature range, ratios of (HCO_3 + CO_3)/Cl range from 24 to 75. Ratios in the warm waters are similar to those of the cold waters in having a wide range within a narrow temperature spread.

The $(HCO_3 + CO_3)/Cl$ ratios confirm other chemical evidence discussed previously suggesting that waters with temperatures greater than 149°F (65°C) are relatively unmixed and probably have been cooled by conduction to the observed temperatures with only minor amounts of mixing. Most waters with temperatures less than about 140°F (60°C), on the other hand, have mixed appreciably with meteoric water, and the $HCO_3 + CO_3$ concentrations are affected by a wide range of local conditions which influence the pH and CO_2 concentrations.

Estimates of Reservoir Temperatures

The solubility of silica in water is highly sensitive to the temperature of the water, and for this reason silica concentrations in thermal waters have been used as a basis for estimating reservoir temperatures (Fournier and Rowe, 1966). Estimates of reservoir temperatures from silica content of ground water are based on the following assumptions: (1) an adequate supply of silica is available in the reservoir rocks; (2) the water has remained in contact with the rocks for a sufficient length of time to reach chemical equilibrium with respect to silica; (3) the silica concentration attained at depth remains constant as the water moves from the reservoir to the sampling point. The third assumption implies that the reservoir water does not mix with water of differing silica concentrations.

In applying the silica geothermometer to waters of the Klamath Falls area, assumption (1) is accepted as true. The silicification of large volumes of rock in the area indicates that silica was abundant in hot waters during earlier times. The silica may have been derived from the deeper rocks of the region or from diatomite in the Tertiary and Quaternary sediments. Because the hot waters are largely isolated from the shallow sediments, silica now present in these waters is probably derived from underlying rocks. Although virtually no quartz is available in the basaltic rocks of the region, the deeply circulating thermal waters may encounter rhyolites of Eocene or Oligocene age, or quartz-rich sediments of Eocene age, both of which underlie younger Tertiary rocks in adjacent areas (Williams, 1949; Peterson and McIntyre, 1970).

In spite of a general availability of silica, the geothermal system could now be largely restricted to flow paths and conduits which have been depleted in silica during what may have been a lengthy existence. There is no evidence of recent silicification such as that found pervasively in the rocks surrounding the geothermal areas, and this may indicate that silica contents as well as flow volumes have decreased during the life of the system. This question has not been resolved by this study. The uniform silica concentrations of the hot waters over a wide area suggest, however, that silica saturation has been generally attained by the thermal waters.

The second assumption relates to the time required to reach equilibrium with silica. No estimates of residence times in the geothermal reservoir have been made for this study, but estimates of hydraulic conductivities and probable minimum travel paths suggest that times may be on the order of tens of years. This conclusion is based partly on the fact that hot waters of similar and unique chemical character are found at places separated by as much as 12 mi (19 km) which suggests that the thermal flow system is relatively deep and extensive. The waters are assumed, therefore, to have sufficient residence time to permit equilibration with silica in the reservoir.

For temperatures common to the hot waters of the Klamath Falls area (125° - 203°F; 70° - 95°C), consideration must be given to the question of whether silica solubilities are controlled by quartz or by more soluble forms such as chalcedony or amorphous silica. The discussion of this question by Fournier and Rowe (1966) and by Fournier (1973) supports the view that control by amorphous silica in hot waters is unlikely. The possibility that the hot waters are in equilibrium with chalcedony is largely ruled out by the fact that calculated reservoir temperatures based on chalcedony equilibria are lower than observed water temperatures. (See fig. 9.) It has not been determined, however, whether more soluble phases of silica such as chalcedony contribute to the total silica contents of the waters.

The third assumption listed above, specifying that silica concentrations remain constant as the thermal waters ascend to the surface, is probably not completely met. To test this possibility, reservoir temperatures were calculated by means of a mixing model. The relatively constant silica concentrations of the hottest waters of the region suggest, however, that the amount of both wall-rock interaction and dilution by mixing is minimal. Support for this conclusion is found in the constant $(HCO_3 + CO_3)/Cl$ relation, the high Na/K ratios, and the low HCO_3/Ca ratios, which confirm the estimates, based on silica contents, of relatively low reservoir temperatures. Silica concentrations, therefore, would not be expected to change appreciably through either precipitation or further solution of silica, and dilution is assumed to be minimal. On the basis of the preceding arguments, the silica concentrations of the hot waters are believed to be fairly reliable indicators of reservoir temperatures.

Several silica geothermometers were given by Fournier and Rowe (1966) and Fournier and Truesdell (1974). Briefly, the four models used for this study make the following assumptions: (1) quartz saturation with adiabatic cooling (Qtz. Adiab.), (2) quartz saturation with conductive cooling (Qtz. Cond.), (3) chalcedony saturation with conductive cooling, and (4) quartz saturation, boiling with removal of steam, and mixing with cold, meteoric water (BSMM). A fifth mixing model that assumes no steam separation (Warm Spring Mixing Model) produced apparent reservoir temperatures of less than 100°C which are not listed here. Computations were made by means of Geoterm, a computer program written by Truesdell (1976). Results are listed in table 8.

Input data for the Boiling Spring Mixing Model included a chloride concentration of 60 mg/l and a temperature of 203°F (95°C) for the hot water, and a silica concentration of 35 mg/l, a chloride concentration of 1 mg/l, and a temperature of 54°F (12°C) for the cold water. The chloride concentration chosen for the hot water is the maximum observed in hot wells in Klamath Falls, and the values of chloride, silica, and temperature chosen for the cold water component are typical of cold waters of the region (Frank and Harris, 1969, table 4; Leonard and Harris, 1974, tables 4-8).

Estimated reservoir temperatures based on the quartz geothermometer are within a narrow range for most of the hot waters, but have a much broader range for the warm waters (table 8). Reservoir temperatures based on chalcedony equilibria are probably not applicable to the waters with measured temperatures greater than about 158°F (70°C), but may be applicable to low-temperature waters. Average reservoir temperatures calculated for the nine hottest waters by means of the quartz (conductive) model range from 255° to 267°F (124° to 131°C). The Boiling Spring Mixing Model largely confirms the quartz conductive model, but the BSMM is not reliable at the indicated low temperatures.

The models based on quartz equilibria, therefore, provide estimates of reservoir temperature which appear to be reasonable and consistent with other chemical data for the hot waters. Quartz is not an abundant mineral in the geologic formations underlying the Klamath Falls area, but it is probable that deeply circulating water would encounter quartz in adequate quantities. If the assumptions underlying the model are met, therefore, calculated reservoir temperatures should be minimum probable temperatures, and actual reservoir temperatures may exceed the estimates. As noted above, however, other chemical characteristics of the waters suggest that reservoir temperatures are not much greater than those calculated from the silica data.

Waters obtained from wells at temperatures less than 150°F (65°C) are almost certainly mixed waters in the Klamath Falls area. When the BSMM is applied to these samples, however, results are highly erratic. The generally high estimated temperatures (397° - 705°F; 203° - 374°C) are caused by extremely low chloride concentrations and relatively high silica concentrations in most of the warm waters. It is clear that these waters do not fit the conditions required for the model.

Estimated reservoir temperatures for a number of warm waters in the Klamath Hills area are extremely low as a result of relatively high chloride concentrations in these waters (wells 45, 51, 56, and 57). These estimates also are probably unreliable. The most likely causes of the failure of the BSMM to provide reasonable estimates are the availability of amorphous silica and the generally unstable, non-equilibrium chemical conditions that prevail in the sediments permeated by the warm waters.

A second quantitative geothermometer that has been applied successfully to geothermal systems is the cation geothermometer of Fournier and Truesdell (1973). Based on data from boiling spring systems such as those in Yellowstone Park, the following empirical expression has been formulated:

$$\log (Na/K) + \beta \log (\sqrt{Ca}/Na) = \frac{1647}{273 + t_{oC}} - 2.24 = K^*,$$

where cation concentrations are in moles , t is temperature in degrees Celsius, β = 4/3 for waters equilibrated at less than 100°C and 1/3 for waters equilibrated at more than 100°C.

In order to test the applicability of the Fournier-Truesdell equation to waters of the Klamath Falls area, data from table 6 were substituted in the equation, and the resulting value of K* for each sample was plotted versus the reciprocal of the measured temperature in degrees Kelvin. The results are shown in figure 12 along with a line representing the Fournier-Truesdell expression. Projection of the K* values horizontally onto the line gives the apparent temperature of equilibrium in the reservoir.

The graph shows that the majority of water samples fall into two groups with similar estimated reservoir temperatures. The left-hand group of open circles comprises the hot waters of the area, and a projection of these points onto the line produces estimated reservoir temperatures that are lower than actual water temperatures. This result is caused by high Na/K and $\sqrt{Ca}/Na$ ratios which place these waters outside the range of use suggested by Fournier and Truesdell for their expression. Thus the cation relations in the Klamath Falls hot waters do not yield reliable estimates of reservoir temperature.

Data points below and to the right of the equilibrium line in figure 12 represent warm, and presumably mixed, waters with wide ranges of concentrations of Na, Ca, and K. Most of these samples provide estimated temperatures of last rock-water equilibrium that are remarkably similar to estimates derived from the hot waters (table 8). Eight samples (solid circles), however, give anomalously high estimates. The position of these points on the graph (figure 12) would be more in accord with the remainder of the data if the value of β were changed from 1/3 to 4/3, but the estimated reservoir temperature would still be very high. This anomalous group includes the warmest waters sampled from areas outside the immediate vicinity of the geothermal zones. The waters have high concentrations of sodium and bicarbonate and high specific conductance, and, except for sample 1 (Eagle Point Spring), they were obtained in fairly deep wells penetrating lake sediments and alluvium. These samples illustrate the complexity of the chemical relations that occur in warm waters percolating through a variety of fine-grained sediments, particularly those containing unstable volcanic glass.

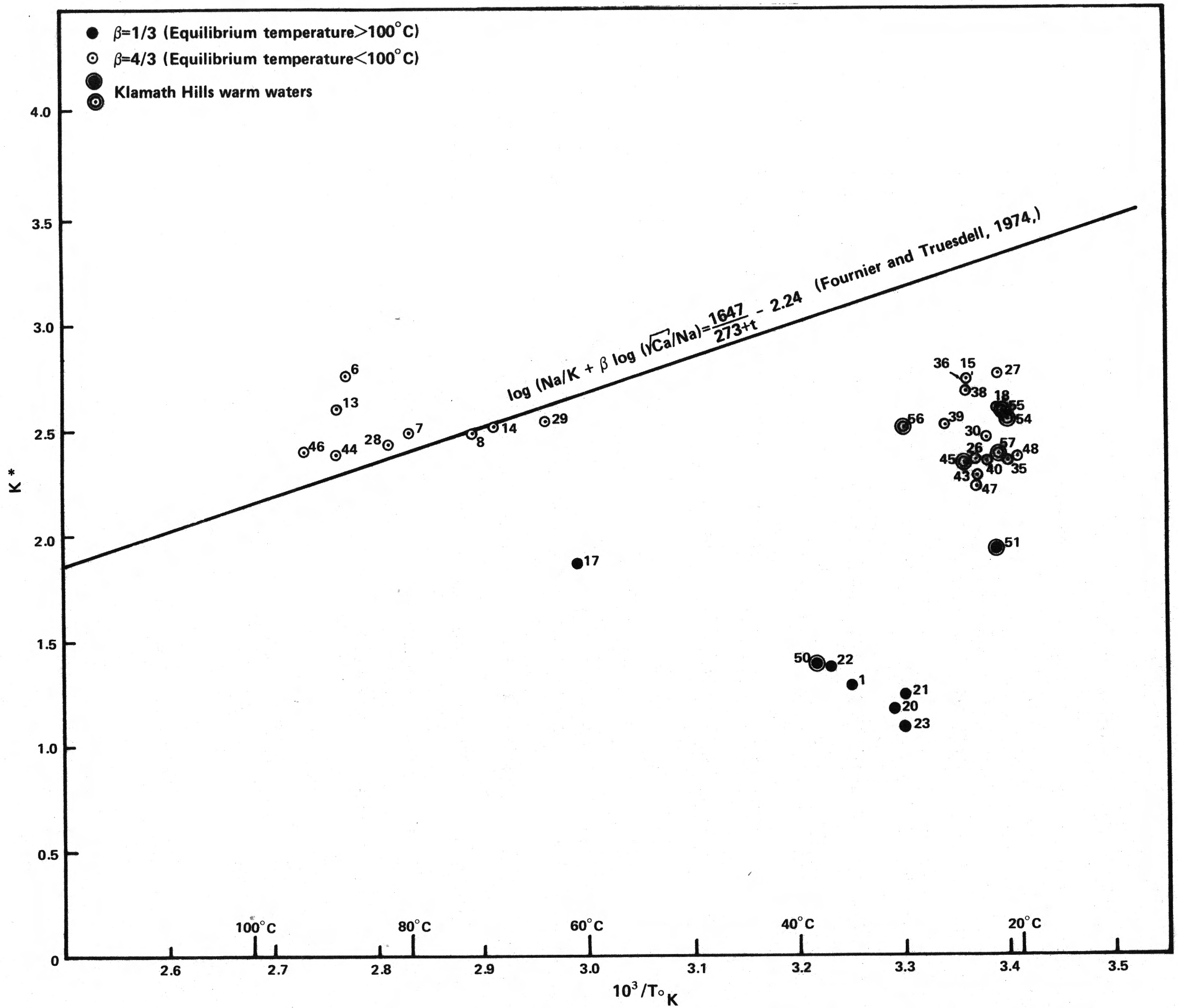

Figure 12. -- Measured temperature (degrees Kelvin) in ground water versus log (Na/K) + β log (√Ca/Na) = K*.

Analyses of Stable Isotopes

Analyses of the stable isotopes of oxygen (^{18}O) and hydrogen (D) have been used to ascertain the origin and history of thermal waters. (See, for example, International Atomic Energy Agency, 1974; Taylor, 1974.) Accordingly, samples of water from a number of wells and springs in the vicinity of Klamath Falls were analyzed for ^{18}O and D (deuterium) concentrations (table 9). In order to view the Klamath Falls results against a regional background, samples of water from wells and springs located in a wide area to the east, north, and west of Klamath Falls were analyzed for ^{18}O.

The amounts of ^{18}O and D in precipitation decrease with altitude in a manner that is approximated by the expression

$$\delta D = 8\ \delta^{18}O - 10$$

where δD and $\delta^{18}O$ are ratios of these isotopes to ^{1}H and ^{16}O, respectively, expressed in parts per thousand as departures from the ratios in Standard Mean Ocean Water (SMOW). The "meteoric line" resulting from the above expression is graphed in figure 13 along with data from 17 springs and wells of the Klamath Falls area.

The $\delta D/\delta^{18}O$ relations shown in the graph of figure 13 demonstrate that the cold, fresh waters of the area, represented by samples 4, 41, and 42, appear to establish a trend parallel to but offset from the theoretical meteoric line. Sample number 1, a spring water having a temperature of 95°F (35°C), is anomalous, possibly as the result of sampling or analytical errors. The hot wells, numbers 6, 7, 13, 28, 44, and 46, are slightly enriched in ^{18}O, but only numbers 13 and 28 (Mills School and Olene Gap Spring) depart appreciably from the background relation established by the cold waters. Samples 13 and 28 are produced by a flowing well and a spring, respectively, whereas the other samples of hot water are from pumped wells. Finally, three warm waters from the Klamath Hills, numbers 45, 51, and 53, show major displacements from the meteoric line, and again demonstrate that these waters differ significantly from both hot waters and other warm waters in the area. The $\delta^{18}O$ in the hot waters increases by about 9% versus 3% for δD. The Klamath Hills warm waters, on the other hand, have increases of as much as 55% in $\delta^{18}O$ (7 per mil) and 40% in δD (15 per mil).

The relation of $\delta^{18}O$ to Cl in ground water of the area is shown in figure 14. Similar trends are shown by $\delta^{18}O$ in relation to SO_4, B, silica, and specific conductance. In general, the $\delta^{18}O$ increases with concentration of the dissolved elements, but the hot waters (represented by samples 6, 7, 13, 28, 44, and 46) form a small cluster whose position indicates that the concentrations of dissolved elements are high relative to cold waters whereas values of $\delta^{18}O$ are about the same as those in cold waters.

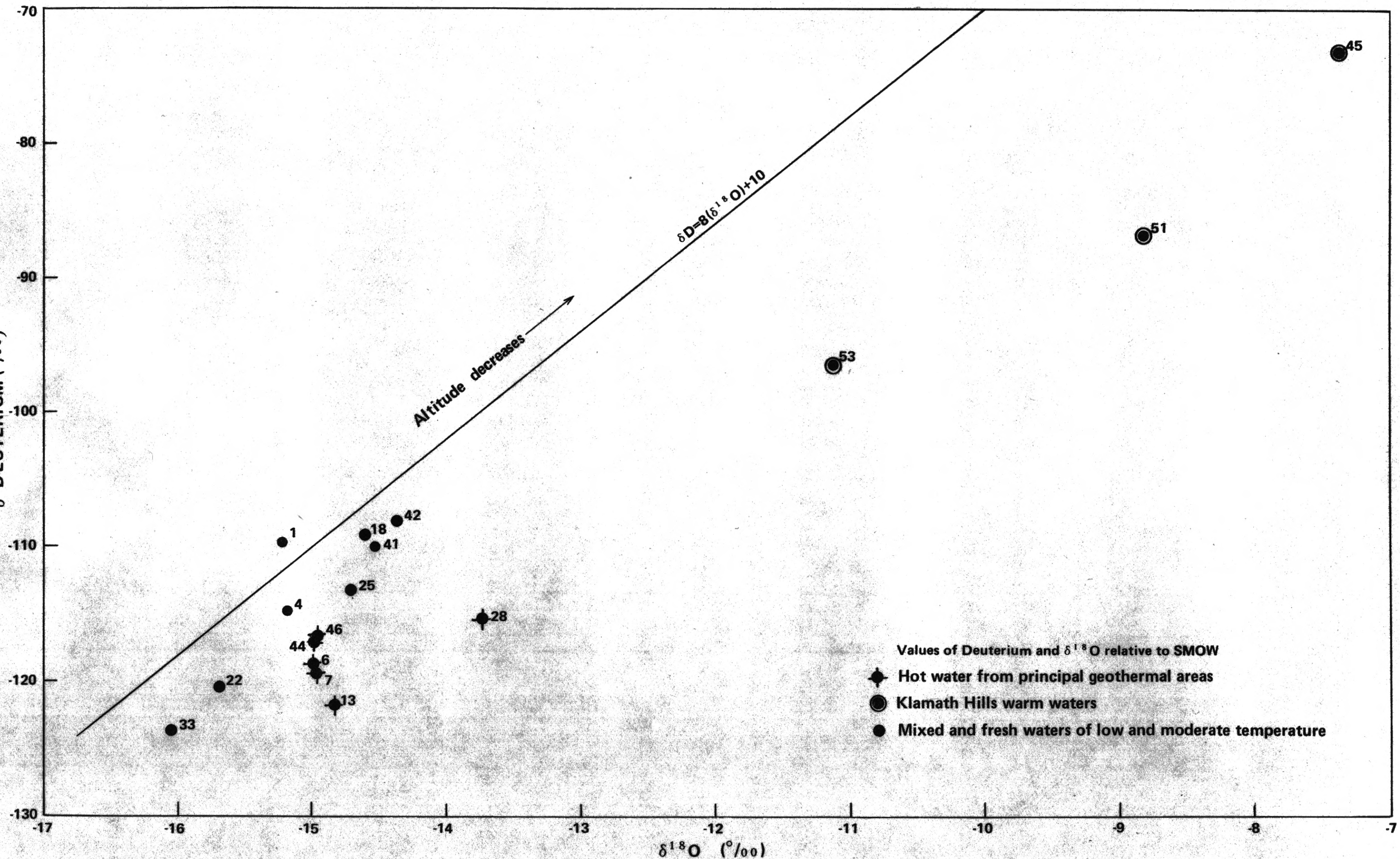

Figure 13. -- $\delta^{18}O$ versus δdeuterium in ground water.

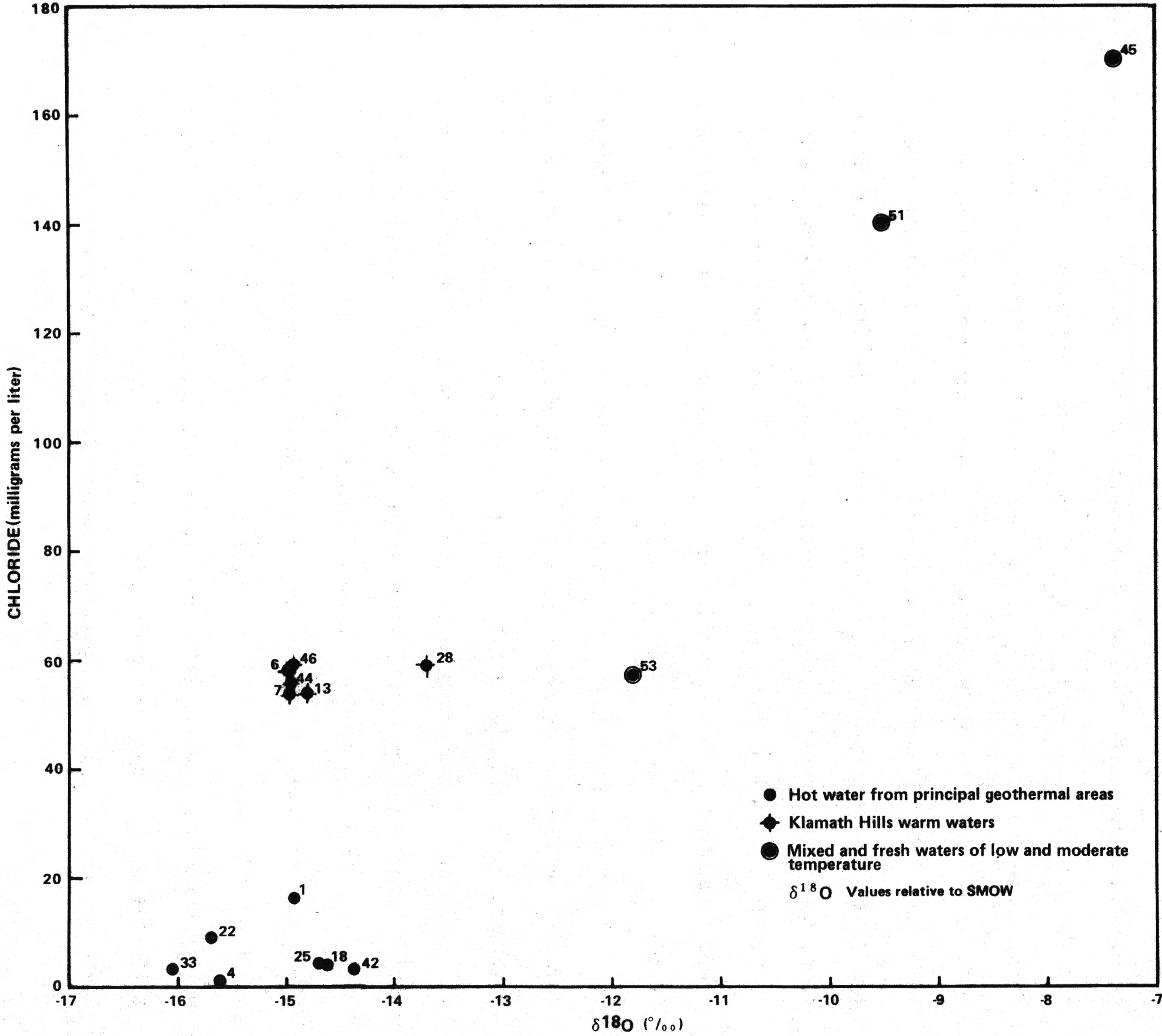

Figure 14. -- Chloride concentration versus $\delta^{18}O$ in ground water.

Results of the isotope analyses are ambiguous. For example, in the graph of $\delta^{18}O$ versus δD (figure 13), it might be possible to extend a regression line through the hot-water data points that would have a slope of approximately 3 and thus would be analogous to relations determined for the acid thermal waters of Lassen Park, the Geysers, and Yellowstone Park. (See Craig, 1963, fig. 5.) This possibility is seemingly ruled out, however, by the near-neutral pH of the Klamath Falls hot water. Three samples of Klamath Hills warm waters (45, 51, and 53) are also ambiguous. They suggest a regression line of slope about 5, comparable to no known geothermal areas but similar to slopes for oil-field brines in California (White, and others, 1973, fig. 3), or the evaporational trend line shown by White (1968, fig. 7) for waters of Steamboat Creek, Nevada.

The most likely possibilities for the significance of the isotope data are believed to be as follows: (1) In figure 13, the samples of hot water (6, 7, 13, 28, 44, and 46) probably represent a $\delta^{18}O$ shift of 1/2 to 1 1/2 per mil analogous to but smaller than those observed in near-neutral chloride-rich waters such as Steamboat Springs, Nevada (White, 1968, fig. 7). Scatter in the data suggests that slightly different chemical conditions obtain in the three separate geothermal areas. (2) Figure 14 indicates that although concentrations of Cl in the hot waters have increased significantly relative to concentrations in the cold waters, $\delta^{18}O$ has increased only slightly, suggesting that the high temperatures required for large-scale exchange of ^{18}O with rock have not been attained (White, 1970, p. 59). (3) The three samples from the Klamath Hills (45, 51, and 53) represent a population of waters different from the normal hot waters and from other warm waters in the area. They probably comprise mixtures of the normal hot waters with meteoric water that has been subjected to low-temperature evaporation in a dry climate. If this supposition is true, there is a strong implication that the meteoric-water component of the Klamath Hills water is derived from local recharge in the closed basin of Lower Klamath Lake.

TEMPERATURE DISTRIBUTION AND HEAT FLOW

Areal Distribution of Temperature

The distribution of temperatures measured in ground water of the Klamath Falls area is shown in figure 15. The isotherms on the map are highly generalized in that they do not reflect increases in temperature corresponding to increases in depth. Thus, for example, at some places located between the 20°C to 30°C isotherms, wells deeper than those sampled may encounter temperatures greater than 30°C. The map is, therefore, only a guide to places where wells of moderate depth (generally 150 to 500 ft; 45 to 150 m) may be expected to encounter temperatures similar to those in existing wells.

The map shows that although warm water occurs at a number of isolated places, the principal occurrences are confined to three areas which have been centers of interest for many years. These geothermal areas are located within the three closed 60°C contour lines on the map. They comprise the Klamath Falls urban area, Olene Gap, and the southwest flank of the Klamath Hills.

Vertical Distribution of Temperature

Temperature profiles were measured in 41 unused, non-flowing wells and in two test holes drilled for the purpose (figure 16). The locations of these holes are shown in figure 4. Significant data pertaining to the profiles are given in table 10, where the profiles have been divided into three groups on the basis of their dominant characteristics: Mainly Conductive Profiles, Cold Convective Profiles, and Irregular Profiles.

Most of the wells in the first group, Mainly Conductive Profiles, penetrate lacustrine sediments of low permeability ranging from silt and clay of Holocene age to shale and diatomite of the Pliocene Yonna Formation. Only three of the holes are known to penetrate basalt. Although the upper parts of the individual profiles are difficult to trace in figure 16, nearly all show evidence of downward convective transport in the upper few tens of feet (few meters). In addition, many have slight temperature irregularities at various depths which, in some instances, correspond to known permeable zones in the rocks.

Wells with nearly uniform conductive thermal gradients have been used to define areas of dominantly conductive heat flow in figure 15. These areas are underlain almost entirely by lacustrine and alluvial sediments and are generally adjacent to the principal geothermal areas.

Thermal gradients in the conductive profiles are generally high, ranging from 50° to 180°C per kilometer (°C km^{-1}), even though temperatures are relatively low. The highest temperature observed was 38°C (100°F) at 500 ft (150 m) in CW 3, located at 39/9-3ddd, just south of Altamont.

The second category of profiles in table 10, Cold Convective Profiles, includes 10 holes in which the profiles are characterized by low temperatures and small thermal gradients. Most of these wells are relatively shallow and are located in the lowlands of the area. Profiles in these wells and test holes show that downward flow of cool water occurs to depths of 300 ft (90 m) at places. They also suggest that the silts and clays of the lake sediments are more permeable than expected, although permeabilities are still relatively low.

Areas where convective flow and cold waters dominate (unpatterned in figure 15) probably are recharge areas. Significant amounts of recharge may also occur in the patterned areas, however, some of which is indicated by wells, such as OCI (3), which have dominantly conductive profiles but show evidence of downward circulation in the upper 50 to 100 ft (15 to 30 m) of the profiles.

One of the deeper wells, OIT 3, shows downward convection to a depth of more than 900 ft (275 m). Well OIT 3, located less than 2,000 ft (600 m) from one of the three hot wells at the Oregon Institute of Technology (figure 6), demonstrates the profound effect exerted by local structure and stratigraphy on subsurface temperature regimes. Although the water level in OIT 3 is an unexplained anomaly (see section on "Occurrence and Movement of Ground Water").the temperature regime may be representative of those in many uplands in the area where significant amounts of recharge occur.

The third category of profiles in table 10, termed "Irregular", includes all the hottest wells in which profiles were obtained. Nearly all the hot wells penetrate basalt flows of the Yonna Formation; probably only two of them, PH 20 and OWC 6, also penetrate older Tertiary basalt.

The three profiles in the upper right corner of figure 16 are probably representative of conditions in rocks of the Yonna Formation near the principal geothermal areas. These profiles, P & F 29, BH 28, and AG 33, show typically high thermal gradients opposite relatively impermeable shales and clays of the Yonna Formation. They show nearly isothermal profiles opposite zones of permeable basalts and associated volcanic sediments underlying the uppermost Yonna rocks. The hot isothermal sections of the profiles suggest that hot water moves laterally in permeable zones, and the prevailing flow gradients (figure 5) indicate that this flow brings about the widespread distribution of warm ground water in the lowlands south of Klamath Falls and Altamont.

Most of the isothermal profiles probably do not accurately represent temperatures in the formations outside the wells. For example, well OC 7 had a measured water temperature during pumping of 37°C (99°F), whereas the temperature profile indicates isothermal conditions at 30°C (86°F). The observed profile clearly is influenced by convective flow in the well; the temperature profile in the formation probably would not be isothermal. Wells OC 1 and KFO 1 have similar discrepancies, and the profiles are thought to be inaccurate as the result of convective flow.

The deepest profiles obtained are from wells PH 20 (1,582 ft; 482 m) and OIT 6 (1,805 ft; 550 m). These two wells are about 500 ft apart. A comparison of the profile measured in PH 20 with the bottom-hole temperatures of OIT 6 suggests that the convex-upward bulge in the profile of PH 20 is the result of convective flow in the well or outside the casing. Thus, the temperature gradients measured between 500 ft (150 m) and 750 ft (230 m) in PH 20 are probably significantly higher than gradients in the surrounding rocks. The approach to an isothermal profile between 1,395 and 1,585 ft (425 and 482 m) is probably also unrelated to gradients in the formation. Similar effects may have occurred in many of the wells measured for this study, and many of the profiles may have significant errors of this kind. Furthermore, the bottom-hole temperatures in OIT 6 show a sharp break near 1,740 ft (530 m) which corresponds to a gravel layer between basalt flows noted in the driller's log at this depth. Small effects of this kind may be difficult to detect in profiles obtained in water-filled holes.

Reported or measured temperatures in several wells are lower under pumping conditions than the maximum temperatures observed in the static profiles. Wells OIT 3, OWC 6, and MB 14, when pumped, appear to derive most of the water from cooler zones in the upper parts of the profile. The observed temperature decreases during pumping may be taken as evidence of the highly stratified occurrence of the thermal and nonthermal waters.

Most hot wells in the vicinity of Klamath Falls and Olene Gap have irregular but generally convex-upward temperature profiles. These profiles probably represent both upward and lateral convective transport of heat in the aquifers. Wells penetrating the Yonna Formation in the Klamath Hills geothermal area would probably show similar profiles. The three areas mentioned are interpreted as thermal discharge areas in figure 15.

A few of the profiles obtained in this study appear to be graded to surface temperatures as high as 25°C (77°F), but the deepest hot wells have profiles which appear to grade to normal surface temperatures for the region (between 8°C and 12°C; 46° and 54°F). Thus far, no measurements have been made at shallow depths in order to determine the distribution of temperatures near the land surface in the geothermal areas. Such a study will, however, be a part of the investigation to be carried out by the Geo-Heat Utilization Center of the Oregon Institute of Technology under a grant from the Geological Survey.

Conductive Heat Flow

Two 600-ft (180-m) holes were drilled by the Geological Survey in the Lower Klamath Lake area in order to obtain heat-flow information. These holes and the data obtained from them are described in detail in Sass and Sammel (1976). The temperature profiles are shown in figure 16. The first hole, JL 1, is on reclaimed marsh land in the Lower Klamath Lake near the California border at 41/8-13acd. The hole penetrated unconsolidated lacustrine sediment, mainly silt and clay, to a depth of 605 ft (184 m). The mean thermal conductivity of cores from the hole was 1.82 mcal cm^{-1} sec^{-1} $^{o}C^{-1}$. For the interval between 167 and 587 ft (50 and 180 m), the average gradient was about 16.75^{o} C km^{-1}. The heat flow at the site, therefore, is calculated to be 0.30 HFU.

The second hole, OC 1(3), was drilled at a location 4.5 mi (7 km) northeast of JL 1, about 1 mi (1.6 km) southwest of the Klamath Hills. For this hole, the mean thermal conductivity was 1.83 mcal cm^{-1} sec^{-1} $^{o}C^{-1}$, the temperature gradient in the interval 174 to 577 ft (53 to 176 m) was 78.6^{o}C km^{-1}, and the heat flow, therefore, is 1.44 HFU.

The heat flow calculated for hole JL1 (0.30 HFU) is too low to be considered representative of actual heat loss from the earth's interior over a broad area. Convective cooling by vertical recharge of ground water to depths greater than 600 ft (180 m) must be invoked to explain the low heat flux to the surface. In the light of data discussed below, the estimated heat flow at JL 1 is anomalous, even for the supposed recharge areas of Lower Klamath Lake.

Heat flow in the second hole, OC 1(3), (1.44 HFU), is near the expected lower limit for conductive heat flow in the Basin and Range province (Sass and others, 1971), and is nearly five times greater than the value calculated for JL 1. The thermal conductivities of the sediments in the two holes are nearly identical, and the geohydrologic settings are apparently similar. The higher heat flow at OC 1(3), therefore, might be due to an influx of hot water from the geothermal area in the Klamath Hills, about 1 mi (1.6 km) distant. The data obtained from the remainder of the conductive temperature profiles suggest, however, that hole OC 1(3) more likely represents near-normal conductive heat flow in sediments of the Lower Klamath Lake basin. The basis for this conclusion is discussed in the following paragraphs.

In order to gain a better understanding of the possible range of heat-flow values in the area, 15 heat-flow values were calculated by combining temperature gradients from 15 conductive temperature profiles with the mean thermal conductivity determined in heat-flow holes JL 1 and OC 1(3). The 15 profiles chosen are designated by asterisks in table 10, and, with the exception of WP (Wiard Park District), are included under the heading "Mainly Conductive Profiles". Each of the wells penetrates unconsolidated to semi-consolidated lacustrine sediments in the Lower Klamath Lake valley. The resulting estimates of heat flow are regarded as minimum values for the sites (Sass and Sammel, 1976, table 2).

Calculated minimum heat flows for the 15 wells range from 0.8 to 3.1 HFU, with the highest values coming from wells nearest the Klamath Falls and Olene Gap thermal areas. Seven of the wells in the Lower Klamath Lake valley are located sufficiently far from both thermal areas and recharge areas to be considered as possibly representative of normal conductive conditions, and these seven wells afforded estimates of heat flow in the range 1.3 to 1.6 HFU. It seems reasonable, therefore, to assume that the calculated heat flow for OC 1(3), (1.44 HFU), does in fact represent "normal" heat flow over much of the Lower Klamath Lake graben.

The wide range of the estimated minimum heat flows for the remainder of the wells tends to confirm the conclusion, drawn from the array of temperature profiles, that localized geologic and hydrologic conditions determine the temperature regime at most places. Many of the profiles that reach relatively high temperatures appear to be influenced by temperature boundaries at the interface between basin sediments and basalt flows. Others are apparently influenced by lateral convective flow of heat and water in permeable zones within the basalt sequences. In general, the observed heat fluxes do not appear to provide information directly related to the source of thermal activity at depth.

Convective Discharge of Heat

Estimates of thermal discharge from springs and wells in the three principal geothermal areas have been calculated from data relating to ground-water discharge and temperatures of the water. The estimates are based on an assumed average temperature of 12°C (54°F) for ground water near the land surface. Results are given in table II.

Table II.--Net thermal flux in ground water discharged from springs and wells in selected areas near Klamath Falls.

	Net Thermal Flux[1] (10^5 calories per second)
Klamath Falls urban area[2]	17.3
Klamath Hills	1.8
Olene Gap	1.0
Upper Klamath Lake (spring discharge)	.3
Total	20.4

[1] Thermal discharge above base of 12°C (54°F) assumed at water table.

[2] Based in part on numbers of wells, flow rates, and temperatures described in Lund and others, 1974.

In the absence of detailed studies, estimation of spring discharge into Upper Klamath Lake is little more than a guess. The remainder of the figures in table II are probably reasonable approximations in the light of presently available data. Estimates for the Klamath Falls urban area will be refined after completion of the current study of the area by the Geo-Heat Utilization Center, Oregon Institute of Technology.

Heat discharged at the air-water interface beneath the land surface by ground water from the three geothermal areas must account for large additional heat fluxes. In assessing this thermal discharge, one may compare the temperature distributions shown in figure 15 with the contour map of the shallow ground-water surface (figure 5). In the vicinity of Klamath Falls, for example, the ground-water contours show that flow occurs into and through the zone of highest temperatures, and that the area in which warm water occurs extends southward across the valley floor into an area where ground-water gradients are very low. Thus, the general picture is one of rapid mixing and initial cooling of the thermal waters in the immediate vicinity of the major thermal zone, with slow convective upwelling and additional cooling in an extended area to the south.

This simple conceptual model is undoubtedly complicated by details of stratified flow of hot water that occurs in basalt flows underlying the Yonna Formation. The general patterns of fluid flow and thermal mixing postulated above are, however, in accord with the evidence of the chemical data, and these patterns are believed to occur in the vicinity of each of the three major thermal areas.

Because the patterns of lateral and vertical convection are complex in detail and are not well known, it is not possible to make a reliable estimate of the total convective heat discharge. By making several reasonable assumptions, however, the available data may yield a crude estimate of the probable range of total heat discharged by convective flow.

An estimate of the total convective heat flux in the vicinity of Klamath Falls was made based on the following assumptions and information. It was assumed that ground-water flow is within 500 ft (150 m) of land surface in the vicinity of the geothermal areas occurs mostly in the Yonna Formation. The transmissivity of the aquifer is estimated to be in the range 500 to 8,000 $ft^2\ day^{-1}$ (45 to 750 $m^2\ day^{-1}$) (table 5). The total length of the three major thermal discharge areas is probably in the range 3 to 5 miles (5 to 8 km), and the ground-water gradients away from these discharge areas may range from 0.0038 to 0.0095 (20 to 50 $ft\ mi^{-1}$; 3.8 to 9.5 $m\ km^{-1}$). Assuming, finally, that ground-water temperature decreases from 95° to $12^{\circ}C$ (203° to $54^{\circ}F$) in the area between the thermal vents and the ultimate discharge points, the probable range of convective heat discharge at the water table is calculated to be 1×10^6 to 50×10^6 $cal\ sec^{-1}$. Combining these figures with the estimate of thermal flow from springs and wells (table 11), the total convective flux in the vicinity of Klamath Falls is estimated to be in the range 3×10^6 to 50×10^6 $cal\ sec^{-1}$.

The range of values given above may be compared with an estimate of geothermal heat being utilized at present for space heating and other purposes. Lund and others (1974, p. 26) estimated that about $1,700 \times 10^8$ BTU per year (1,340 calories per second) are currently utilized in some manner. The geothermal heat actually used is, therefore, an insignificant fraction of the heat now being discharged by natural or artificial means in the Klamath Falls area.

INTERPRETATIONS AND CONCLUSIONS

Review of Evidence Relating to the Geothermal Resource

Geologic Evidence

Volcanic rocks in the vicinity of Klamath Falls are all relatively young, and some are probably as young as late Pleistocene. Holocene flows and pyroclastic rocks crop out both north (Crater Lake) and south (Lava Beds National Monument) of Klamath Falls. There are, however, no known manifestations of rock bodies that retain significant magmatic heat at relatively shallow depth in the Klamath Falls area. Thus, this area is unlike electric-power producing geothermal systems elsewhere, where hot intrusive masses at depth are the likely heat source.

A recent study by MacLeod, Walker, and McKee (1975) shows that silicic volcanic activity in southeast Oregon during the past 10 million years or more was progressively younger from east to west, culminating at Newberry Volcano, near Bend, in the extrusion of rhyolite domes with ages about one-half million years, and obsidian flows less than 10,000 years old. Projection of the age contours established by that study into the Klamath Falls area indicates that if silicic masses occur at depth near Klamath Falls they should be about 4 million years old. On the basis of calculations made by Lachenbruch and others (1976) for Long Valley, California, it is concluded that domal masses of that age and of reasonable size would have cooled to near ambient temperatures by the present time.

The geologic evidence suggests, therefore, that if an intrusive body is the ultimate source of heat for the geothermal phenomena at Klamath Falls, it would most likely be of basaltic composition. Geophysical evidence, discussed in the next section and presented in detail in an appendix to this report, however, confirms the chemical evidence in suggesting that most or all of the thermal manifestations in the Klamath Falls area relate to deep circulation of water in an area of near-normal heat flow and that no magmatic heat is involved in the geothermal system.

Geophysical Evidence

Direct geophysical evidence relating to the geothermal phenomena consists mainly of temperature measurements in water-filled drill holes or water wells. Ground-water temperatures are warmer than normal at many places in the Lower Klamath Lake basin between Klamath Falls and the Klamath Hills, and the temperatures of individual wells are clearly influenced by proximity to the principal geothermal areas. Thermal gradients are relatively high near the geothermal areas, but except for the area directly south of Klamath Falls, temperatures of shallow ground water decline to within 18°F (10°C) of normal in distances of a few thousand feel (one kilometer) or less from known centers of geothermal fluid discharge. Present natural subsurface flow of hot water, therefore, probably emanates from areally restricted elongate zones associated with major faults. Few thermal springs exist, and most of the hot water discharges below land surface where it mixes with local ground water.

Temperature profiles obtained in unused wells and in two drilled heat-flow holes demonstrate that temperature gradients in all parts of the area are strongly influenced by vertical or lateral convective heat transport and are not useful for conductive heat-flow estimates. Nevertheless, a few conductive gradients obtained in Lower Klamath Lake basin suggest that heat flow through the lake sediments may be on the order of 1 1/2 HFU. This value is at the low end of expected values for the Basin and Range province. Although this evidence cannot be considered highly reliable, it does not suggest that a large mass of rock that has retained significant amounts of magmatic heat exists at shallow depth beneath the Klamath Falls graben.

In each of the wells where high temperature gradients are found, it is known or suspected that the gradients are controlled by temperature boundaries at the interface between basin sediments and basalt flows, or that the high temperatures are due to lateral flow of heat and water in permeable zones within the basalts. These profiles provide information on the functioning of the shallow convective part of the geothermal system, but they do not aid in attempts to understand the origin and extent of the geothermal source.

Indirect geophysical evidence relating to the nature of the geothermal resource was obtained from gravity and aeromagnetic surveys. These are reported on and interpreted by D.L. Peterson in a section of this report. In general, the gravity and aeromagnetic trends coincide with the obvious northwest-southeast fault trend through the area. Most of the lowlands are sunken blocks covered by great thicknesses of low-density sediments and bounded by steeply-dipping normal faults. Gravity modeling suggests, for example, that the graben structure may be 3,000 ft (900 m) deep in the area southeast of Klamath Falls and may be more than twice as deep southwest of the Klamath Hills. Gravity highs, such as the one in the vicinity of Klamath Falls, suggest that rocks of relatively high density are near the surface in these places. All the major thermal zones occur either in areas not covered by thick valley fill or immediately adjacent to outcrops of basement rocks.

The gravity data also indicate the presence of structures that may be only suspected from other evidence. Examples are a northeast-southwest trending fault passing through Olene Gap and an east-west trending fault near the north end of Upper Klamath Lake. A major anomaly in the area southwest of Keno may be related to rocks of the adjacent eruptive center.

Peterson's interpretation of the aeromagnetic map indicates that most magnetic anomalies probably relate to the same causative bodies as the gravity anomalies. For example, gravity and magnetic lows occur over the deep structural depression in the Lower Klamath Lake basin. In addition, the magnetic anomalies suggest the presence of surface and near-surface basaltic rocks at many places where these rocks contrast with valley-fill deposits. Prominent magnetic highs over Squaw Point in Upper Klamath Lake and in Lower Klamath Lake east of Keno may represent buried flow rocks.

The gravity and magnetic data over the broad valleys outline a subsurface pattern which at many places is in marked contrast to the nearly featureless valley floor. Transecting faults apparently offset the basement topography in a quilt-like pattern of tilted blocks, some of which underlie the valley at shallow depths whereas others are deeply buried. Basalt flows within the valley fill add to the complexity of the geophysical patterns.

The hydrologic consequences of these displacements are many. The boundaries of the lithologic units may be relatively impermeable at places, thereby contributing to the segregation of waters of differing chemical quality. At other places, basalt flows and fault zones probably form distribution channels for thermal waters. These phenomena are not well known in detail, but they will have important consequences for the withdrawal of thermal waters and recharge to the thermal reservoir.

Hydraulic Evidence

Thermal discharge.--The discharge conduits that produce hot water appear to be hydraulically isolated from the shallow ground-water system in their vicinity. The hydraulic evidence for this assertion is clear for only one of the three geothermal areas, but chemical data from the three zones are similar and tend to support this view. Thus, static water levels in hot wells at OIT and the Presbyterian Hospital are discordant with the surrounding water table, and the chemical characteristics of the hot water clearly distinguish it from the cold water. The very similar chemical nature of the water from Olene Gap and the Klamath Hills suggest, by analogy, that aquifers supplying these springs and wells are also hydraulically isolated from the shallow waters.

Additional evidence from a pumping test shows that at the OIT site the hot-water aquifer may have a higher hydraulic conductivity than the surrounding cold-water-bearing rocks. Rates of pumping from the hot wells at the Klamath Hills suggest that at this site also the thermal aquifer is more permeable than typical basalt aquifers near Klamath Falls.

It is concluded on the basis of hydraulic evidence and the locations of the geothermal areas that the hot waters rise from depth through conduits associated with major faults. These conduits may be the few permeable channels remaining of many that formerly existed during the period when large-scale silicification of the country rock occurred.

The present channels have probably been largely sealed off from the surrounding rocks by deposition of silica. Thus, the term "aquifer" used above in connection with the apparent hydraulic conductivity of the hot-water zone is probably a misnomer. Observations of flow rates, pumping rates, and drawdowns may relate only to hydraulic conditions in the upper part of the distribution system rather than conditions in the thermal aquifers or reservoir.

Recharge to the thermal system.--Temperature profiles that show downward convective flow indicate that meteoric water recharges the shallow ground-water reservoir over large areas of both uplands and lowlands. Little of this widespread recharge reaches the lower aquifers, however. Hydraulic heads in all the deepest wells inventoried for this study are lower than heads in the surrounding shallow aquifers, thus indicating that vertical transport is impeded by low hydraulic conductivities. The recharge potential, however, is large. Few data are available from higher elevations on the upraised fault blocks, but the available data suggest that the highlands are relatively permeable to vertical flow.

On the basis of chemical characteristics, the hot waters of the area are assumed to originate as meteoric water, but analyses of shallow ground water from areas within a 50-mile radius of Klamath Falls show that most ground waters in the region have similar chemical compositions. The precise origins of the water thus cannot be ascertained. In the absence of analyses of additional isotopes such as tritium, the isotope data also are not helpful in defining recharge areas.

Postulated modes of recharge will obviously depend greatly on the assumed depth, nature, and extent of the geothermal source, and in the absence of definitive data on the geothermal reservoir no conclusions have been reached regarding the source and extent of recharge. In general, however, recharge may occur through the same fault systems that act as conduits for the hot water, although it seems unlikely that downward flow would be confined to isolated channels as the thermal discharge appears to be. Rather, the recharge may consist of slow, diffuse seepage through large areas in the fault zones, perhaps far from the discharge sites.

Quantities of water available for recharge are large if the area of potential recharge is assumed to extend to a radius of, say, 25 mi (40 km) from the center of the three geothermal areas. Over this area precipitation is about 2.4×10^6 acre-ft yr^{-1} (3×10^9 m^3 yr^{-1}), of which about 2.1×10^6 acre-ft yr^{-1} (2.6×10^9 m^3 yr^{-1}) is lost through evapotranspiration and the remainder leaves the basin as runoff. It is likely, of course, that only a small part of this water can be captured in the areas of recharge that directly feed the geothermal system, but, nevertheless, a large amount of water is available.

Ground-water flow into the Lower Klamath Lake basin from upper basins may be as much as 170,000 acre-ft yr^{-1} (2×10^8 m^3 yr^{-1}), and this flow may represent a major source of recharge to the geothermal reservoir. Because the Klamath Falls area is a major structural depression, ground-water flow in the upper few thousands of feet (one kilometer) of rock may enter the area from all directions, although scanty observations suggest that there is an overall gradient toward the southwest. A deep regional flow system may bring ground water into the area from the High Cascades, but the writer is not aware of any firm evidence for such flow.

Chemical Evidence

Hot waters from each of the three geothermal areas near Klamath Falls have nearly identical chemical compositions that sharply distinguish them from local meteoric water. Na and SO_4 ions are dominant in the hot waters, whereas Ca and HCO_3 ions are dominant in the cold waters.

Chemical analyses show that between the cold and the hot waters, ratios of Cl/SO_4 and Cl/B do not change significantly within the limits of analytical error for very low concentrations of these constitutents. On the other hand, in the hot waters Na is high relative to K, Ca, and $(Cl + HCO_3 + CO_3)$, Cl is high relative to $(HCO_3 + CO_3)$, and Ca is high relative to Mg. Absolute increases in Na, SO_4, and silica and a decrease in HCO_3 are the dominant changes as the regional cold waters are heated in the geothermal system.

The similarity in chemical characteristics of all the hot waters and their somewhat unusual character indicate that they have similar geothermal environments and histories. The close agreement of temperatures, dissolved solids, and concentrations of silica, SO_4, Cl, B, and $\delta^{18}O$ argue at the very least for passage through nearly identical rocks that occur at similar depths and temperatures.

On the basis of the chemical data, the reservoir appears to be predominantly a hot-water system of moderate temperature. Cl/B ratios indicate that the water is probably heated mainly by conduction and not by condensation of steam from an underlying vapor-dominated system. Hot waters rising from the reservoir in the principal conduits probably cool largely by conduction with little loss of volatile elements.

Because the constituents of the hot waters probably do not change appreciably as the waters rise to the surface, the observed compositions may represent very nearly those of the reservoir fluid. Moderately low HCO_3/Ca ratios and high Na/K ratios indicate qualitatively that the waters equilibrated at temperatures that are low relative to those in many geothermal reservoirs. The silica geothermometer of Fournier and Truesdell (1974) is probably applicable to these waters, and the estimated minimum reservoir temperature is about 266°F (130°C). The actual reservoir temperature is probably not much higher than the estimated value, and is not likely to be within the range considered desirable at present for single-fluid power production methods.

Analyses of the stable isotopes, deuterium and ^{18}O, confirm other chemical data in indicating that the hot waters of the Klamath Falls geothermal areas have equilibrated at low reservoir temperatures. The isotope results suggest also, although not without ambiguity, that the $\delta D/\delta^{18}O$ relation may be comparable to those observed in near-neutral chloride-rich thermal waters such as those at Steamboat Springs, Nevada.

A few samples of water from warm wells on the flanks of the Klamath Hills have silica, Cl, and B concentrations equal to or greater than concentrations in the hot waters. High Cl/SO_4 ratios, low Na/Cl ratios, and relatively high δD and $\delta^{18}O$ values also seem to differentiate these waters from the hot waters of the geothermal areas and from warm waters elsewhere in the area.

The chemical evidence is consistent, but it does not clearly indicate the nature and origin of the Klamath Hills warm waters. The data suggest, however, that these waters represent mixtures of hot water from the Klamath Hills geothermal area and meteoric water that has been subjected to evaporation in the closed basin of Lower Klamath Lake. The mixing probably occurs in the upper 500 ft (150 m) of the aquifers as the hot waters spread from fault-related conduits in the Klamath Hills.

CONCEPTUAL MODEL OF THE GEOTHERMAL SYSTEM

The deep geothermal system at Klamath Falls has not been explored, and only near-surface indications and geophysical data provide indirect evidence of the deeper part of the system. Many of these indications have been examined during this study, and an attempt has been made to synthesize the available data in a conceptual model. The model probably can only be tested with new data, praticularly information derived from deep drill holes.

Geothermal phenomena at the earth's surface theoretically may be produced by three types of systems which have the following three fundamental causes: (1) intrusion of a mass of molten rock into the near-surface rocks; (2) convective transport of heat and fluids from depth in a cyclic system; and (3) blocking of the earth's normal vertical heat flow by layers of rock having low thermal conductivities. Although each of these types of systems may produce abnormal temperature gradients near the earth's surface, only the first is necessarily accompanied by higher than normal conductive heat flows. Actual geothermal systems probably always consist of a combination of at least two of the theoretical types.

On the basis of the evidence gathered during this study, it is concluded that the geothermal system at Klamath Falls represents a combination of the second and third types of systems listed above. The question of the presence of a hot igneous mass is left unresolved because there is no conclusive evidence for such hot bodies and they are not required in order to explain the observations.

Regional heat flow in the Klamath Falls area has been tentatively concluded to be about average for the Basin and Range province; that is, between one and one-half and two HUF. On this basis, the temperature gradient in the earth's crust beneath Klamath Falls may be in the range 30 to 40 ^{o}C/km. If this were true, and if only conductive heat flow were present, the reservoir temperature of 266^{o}F (130^{o}C) estimated for the hot waters could be attained by circulation of meteoric water to depths between 10,600 and 14,200 ft (3,230 and 4,330 m). In the light of the geophysical evidence at Klamath Falls and by analogy with known or assumed conditions in other Basin and Range geothermal systems (White, 1968), depths of circulation of this magnitude are believed to be attainable.

The model proposed for the Klamath Falls geothermal system is, therefore, a very simple one. Meteoric water in the deep regional flow system is assumed to percolate downward along the vast network of intersecting fracture zones that characterize the regional structure. As a result of the alignment of the structural pattern in northwest-southeast trends, most of the water probably flows from the northwest into the troughs formed by the Upper and Lower Klamath Lake basins.

The depths to which the water penetrates are sufficient to raise its temperature to at least 266^{o}F (130^{o}C). As noted above, these depths may be as great as 14,000 ft (4,300 m) or more if a normal conductive temperature gradient is present in the crustal rocks. At Klamath Falls, however, required depths of circulation may be somewhat shallower than the estimated maximum as a result of the blocking of normal heat flow by shallow rocks of low thermal conductivity. Both low-density Holocene sediments and the shales and clays of the Yonna Formation tend to insulate rocks underlying the grabens, and the large sunken blocks of the Upper and Lower Lake grabens probably act as thermal plugs in the heat-flow system. Within and beneath the grabens, isotherms would tend to be displaced upward, and assuming that offsetting topographic effects of the adjacent ridges are smaller than effects of the sunken blocks, temperatures at any given depth may be higher than normal. Thermal gradients would, therefore, be relatively high in the rocks of low thermal conductivity.

Although the general structural and lithologic conditions postulated above probably exist in several of the adjacent basins as well as at Klamath Falls, conditions for the upward flow of heated water from the geothermal reservoir are apparently especially favorable at Klamath Falls. These favorable conditions may relate both to the elevation of the isotherms in a large volume of rock and to the presence of relatively permeable flow channels in parts of the area. The fault-related conduits that permit reasonably free upward convective flow of hot water at three separated places in the vicinity of Klamath Falls may represent vestiges of the extensive and active hot-water system that must have operated to silicify some thousands of cubic meters of rock during Pleistocene or earlier time.

At present, the rising hot waters are probably largely confined to the conduits in the three principal thermal areas, with only minor amounts of upward flow occurring in fracture zones in the interior of the valleys. The sediments that occupy the valley bottoms apparently act as effective hydraulic seals as well as thermal insulators.

The water chemistry and isotope concentrations in the hot waters of Klamath Falls suggest that the widely occurring thermal waters originate in a common reservoir under relatively uniform conditions. Although the possibility of separate origins cannot be ruled out, it seems likely that the meteoric waters circulate in a continuous sequence of Tertiary basalts and volcanic sediments underlying the Upper and Lower Klamath Lake basins and adjacent ridges. The depth and thickness of the rocks comprising the reservoir are unknown, and their lateral extent can only be surmised on the basis of the uniform characteristics of the hot waters.

Based on the extent of the surface manifestations, the reservoir is assumed to extend over an area of at least 100 mi^2 (260 km^2). Beneath the Lower Klamath Lake basin the top of the zone of active convection may be as deep as 5,000 to 6,000 ft (2 km), although beneath the upraised fault blocks depths to the top of the reservoir may be 2,000 ft (600 m) or less at places.

Within the reservoir, the meteoric water dissolves silica, Na, and Cl and becomes greatly enriched in SO_4. HCO_3 decreases and Ca increases relative to Mg, but the ratios Cl/SO_4 and Cl/B do not change significantly. Thus, there is no evidence in these relations for appreciable vaporization of the hot water or heating by steam from a deeper reservoir.

Most of the heated water rising from the reservoir does not reach land surface, but spreads through thin permeable zones in basalts within the Yonna Formation. In these strata, which occur at depths ranging from a few tens of feet to at least 1,500 feet (few meters to 460 m), the flow is predominantly lateral, following local gradients in the shallow ground-water reservoir. The hot water mixes with the local meteoric water and rapidly loses heat. Within one-half mile (1 km) of the major conduits temperatures of the water may decrease about 108°F (60°C), and the chemical nature of the water changes markedly. Ca and HCO_3 increase rapidly and Na and SO_4 decrease. Variations in chemistry are large from place to place in response to local differences in lithology and hydraulic conditions. In general, however, waters found within an area of a few square miles have similar chemical composition.

One of the readily observable consequences of the spread of hot water near the geothermal zones is a notable variation in temperature gradients in the upper 1,500 ft (460 m) of rock. Conductive gradients may be extremely high (>150^{o}C/km) in impervious rocks of the Yonna Formation where these rocks overlie basalts or permeable gravels bearing hot water. At other places where Yonna Formation is more permeable, temperature profiles may be nearly isothermal, and gradients may even be reversed beneath hot-water zones. Thus, most of the temperature profiles in the upper 2,000 ft (600 m) or more of rocks in the Klamath Falls area represent only local distortions of the earth's thermal gradient resulting from convective transport of heat.

An example relating to the restricted occurrence of the upper reservoir is found at Miller Hill, a small upraised fault block about 5 mi (8 km) south of Klamath Falls. Thermal manifestations at Miller Hill are confined to moderately warm, mixed waters encountered at depths of 600 to 800 ft (180 to 240 km). This area, which is near the center of the triangle formed by the three major geothermal zones, apparently has only poor hydraulic connections to the upper hot-water zone, and there are no indications of unusually warm waters in the surrounding area. In contrast, at a smaller unnamed hill about 2 mi (3.2 km) south of Klamath Falls, wells about 400 ft (120 m) deep near probable faults reportedly encounter somewhat warmer water. In the light of the numerous and extensive major faults in the area and the small extent of the thermal emanations, it seems clear that the conditions which would permit upward movement of hot water are relatively rare.

The conceptual model described above requires that heat flow be generally low in the thick valley-fill sections of the area, and the evidence from two heat-flow holes and numerous temperature gradients seems to fit this requirement. The model also requires that heat flow be relatively high on the periphery of the basin as the result of displacement of heat-flow lines by the low-conductivity sediments. This effect is probably masked by convective heat flow in areas near the major geothermal zones, but it may be detectable in the western and southern ridges where convective heat flow is apparently minimal. Finally, the model implies that the concentration and discharge of normal crustal heat flow by convection in a restricted area such as Klamath Falls may result in a deficit of heat flow in the surrounding region.

As a rough check on the regional heat-flow balance, assume that conductive heat flow is in the lower range of expected values for the Basin and Range province, or about 1.5 HFU. Over the approximately 100 mi^2 (260 km^2) of the Klamath Falls thermal area, total conductive heat flow is, therefore, calculated to be 3.9×10^6 cal sec^{-1}. This figure may be compared with the estimates of convective thermal discharge given earlier, which indicate that convective discharge from the Klamath Falls thermal areas is probably in the range 3×10^6 to 50×10^6 cal sec^{-1}. According to these estimates, therefore, most or all the normal heat flow through the crust in this area is concentrated by convective discharge in the three geothermal areas. Even a doubling of the assumed conductive heat flow would still place the value within the probable limits of the estimated convective discharge. Uncertainty in the estimate of convective discharge is large, but even were the actual discharge smaller than the estimate by an order of magnitude, the regional conductive heat-flow patterns must be significantly altered.

Two alternative explanations for these observations are available. Either a magmatic source of additional heat exists beneath the area or conductive heat flow is significantly depleted over a region which probably extends beyond the area of the principal geothermal areas. Although the writer considers the latter conclusion more likely, the facts can be ascertained only by additional exploration, by obtaining more complete chemical data, and by subjecting the data to more sophisticated analysis. Deep electrical soundings may be useful, but exploratory drilling to depths of 5,000 ft (1,500 m) or more may be required in order to provide definitive answers to the questions remaining.

Magnitude of the Geothermal Resource

On the basis of scanty data available to them, Renner, White, and Williams (1975) estimated the amount of heat stored in the Klamath Falls geothermal system down to a depth of 3 km to be 30×10^{18} cal. The assumptions used include an estimated reservoir temperature of 120°C, a reservoir volume of 480 km^3 within 3 km of land surface, and a specific heat content of 0.6 cal cm^{-3} $°C^{-1}$. The estimated heat content places the Klamath Falls system among the 5 largest known geothermal systems in the United States, excluding the Gulf Coast geopressured areas.

On the basis of the additional data obtained in this study, the writer estimates the maximum probable heat content to be 36×10^{18} cal. The assumptions are as follows: (1) a reservoir temperature of 130°C; (2) an area of 260 km^2; (3) a reservoir thickness of 2 km between 1 km and 3 km; and (4) a specific heatof 0.6 cal cm^{-3} $°C^{-1}$. The only departures from the assumptions used by Renner, White and Williams, are the estimated temperature of 130°C rather than 120°C and a slightly larger area.

For this estimate, the reservoir is assumed to comprise a continuous volume of basaltic rock in which hot water moves through fractured layers and interconnecting fault zones. Temperatures in the reservoir are high as the result of convective flow from great depths and the blanketing effect of overlying thick lacustrine sediments of low thermal and hydraulic conductivity. Upward leakage of thermal waters from the reservoir is probably widespread at the base of the sediments, but most discharge of thermal waters occurs through fault-zone conduits in the three geothermal areas.

For an estimate of a probable minimum reservoir volume, it is assumed that the upper parts of the system are restricted to three more or less separate conduit systems with a small amount of interconnection at depth. On this basis, the reservoir may occupy an area of 170 km^2 and have a thickness of 1 km. The resulting volume is 170 km^3. With these assumptions the amount of stored heat is calculated to be 12×10^{18} cal.

For this minimum estimate, the reservoir is assumed to be restricted to areas immediately surrounding the three thermal areas. The change in thickness from the maximum estimate represents largely a lowering of the 130°C isotherm to greater depths beneath the graben floors in order to meet an apparent requirement that heat-flow is relatively low in the valleys. Thus, a greater thickness of rock is available above the reservoir for lateral convective transfer of heat and its accumulation in the vicinity of the geothermal areas. Neither of the above estimates is based on well-defined reservoir geometries or precise flow patterns. Rather, they are attempts to assign reasonable limits to the overall size and type of reservoir which might produce the observed geothermal phenomena.

As is true for any of the low-temperature convective hydrothermal systems, exploitation of the Klamath Falls geothermal resource for electrical power is economically marginal under present conditions, and future utilization would be highly sensitive to the actual nature and extent of the reservoir.

In considering non-electrical uses of the resource, it would be difficult to predict probable benefits even if the geothermal system were better known. As pointed out by Nathenson and Muffler (1975, p. 116), "Until a specific use is chosen for such systems, the fraction of the energy that can be applied to beneficial use cannot be specified." Following approaches described by Nathenson and Muffler, it is possible, however, to place the above estimates of total heat contents into a better prospective. Defining beneficial heat as "thermal energy that can be applied directly to its intended non-electrical use, " using Nathenson and Muffler's assumption that one-fourth of the stored energy is recoverable at the surface and that efficiency of utilization is also one-fourth, and taking an average of the writer's two estimates of heat content, beneficial heat from the Klamath Falls system is calculated to be $\frac{1}{4} \times \frac{1}{4} \times 24 \times 10^{18} = 1.5 \times 10^{18}$ calories. If this useable heat were to be supplied by electrical energy, it would require 1.5 x 1,327 = 1,990 MW-century. Thus, as Nathenson and Muffler remark regarding the total convective hydrothermal resources of the country,"... if the institutional problems can be resolved, this resource has significant potential."

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PRELIMINARY INTERPRETATION OF GEOPHYSICAL DATA

By

Donald L. Peterson

INTRODUCTION

Data from 232 gravity stations have been used to prepare the complete Bouguer gravity map (fig. 17) of the Klamath Falls region. During 1974-75, 103 stations were established by the U.S. Geological Survey and 129 stations by the University of Oregon. Most vertical and horizontal positions are from control points marked on topographic maps at scales of 1:62,500 and from plane-table surveying. Vertical positions for 23 U.S. Geological Survey stations in areas of low relief were determined with altimetry and from map contours. The gravity stations were corrected for topography for a distance of 167 km by a method described by Plouff (1966). A density of 2.67 g/cm^3 was assumed for the material between sea level and station elevations in reducing the data to the complete Bouguer anomaly. However, because the thick sequence of volcanic rock in the area probably has a smaller mean density, the anomaly amplitudes and configurations may be slightly distorted. Theoretical gravity was computed from the 1967 Geodetic Reference System, 1971. The gravity data are referenced to Department of Defense base station (code nos. ACIC 1300-2 and IGB 15721B, 1971) at the Klamath Falls Court House with a value of 979995.61 mgals.

The total-intensity aeromagnetic data (fig. 18) are part of a survey flown in 1972 (U.S. Geol. Survey, 1972). The survey was flown at a barometric elevation of 9,000 ft above sea level. Flight lines were flown in east-west direction at a spacing of about 2 mi.

No measurements were made of rock densities or magnetic properties. The more significant gravity anomalies probably relate to structural features and thickness of valley-fill. The magnetic anomalies are attributed either to structural features or to near-surface volcanic rocks.

Massive volcanic rock or pre-Tertiary, buried rock are referred to as "bedrock" in this section.

DISCUSSION

The gravity anomalies trend mainly northwesterly, northeasterly, and east-west. The northwesterly trend is predominating and is coincident with the structural grain of the area.

A northeast gravity gradient passes through Olene Gap, along the northwest edge of Nuss Lake, and to the Klamath Hills. This gradient suggests a fault zone. A gravity saddle lies a short distance southeast of the gradient between Stukel Mountain and the Klamath Hills and may reflect the upthrown side of the inferred fault zone. The steep gradient bounding the northwestern edge of Lower Klamath Lake may be a southerly extension of the trend; however, it is displaced northwestward about 2 km and its dip is in the opposite direction from that of the gradient northeast of the Klamath Hills.

An eastwest-trending gravity gradient, dipping to the north, is shown in the northwest corner of the map (fig. 17). This gradient is interpreted to reflect a fault zone which is believed to continue eastward for a considerable distance. The gradient is on strike with a topographic trend which extends about 65 km eastward.

The magnetic data also display northwesterly, northeasterly, and east-west trends. The gravity and magnetic trends appear to be continuous from the highlands and across the valley lowlands; however, the trends over the highlands and lowlands are, in most part, difficult to correlate with each other. The gravity and magnetic anomalies appear to be interrupted approximately along the course of the Klamath River. A fracture-zone may lie along the Klamath River; however, more information is needed to confirm this.

A broad magnetic high, about 22 km in length and 8 km wide trends northeastward from the eastern edge of Klamath Falls, and through Swan Lake Valley. The magnetic high is approximately on strike with the Klamath River. Three positive closures are situated on the high. The source of the high is not known with any certainty. A rough analysis of the gradients by means of the method of Vacquier, Steenland, Henderson, and Zietz (1951) flanking the three positive closures indicate the source of the high is not known with any certainty. A rough analysis of the gradients by means of the method of Vacquier, Steenland, Henderson, and Zietz (1951) flanking the three positive closures indicate the source of the anomaly to lie somewhere between the ground surface to 2,500 feet below the surface. The magnetic high may reflect a buried, intrusive, igneous mass with three apophyses.

Two other closed, magnetic highs are located in the study area, which may also reflect buried igneous bodies; one is over Sqaw Point, northeast of Howard Bay, and the other is 3 km east of Keno. The high near Keno can be traced eastward for several kilometers with diminished amplitude. The fact that both highs occur over topographically low, water- and allüvium-covered areas, supports a buried, igneous source.

A linear, irregular, gravity high crosses the map from near the northern edge of White Lake, over the Klamath Hills, and passes between Round Lake and Long Lake Valley to the western edge of the study area. The anomaly is interpreted to reflect a structural high. A steeply dipping gradient bounds the southwestern edge of the high along the edge of the Klamath Hills and suggests a prominent, high-angle fault zone.

Northwest of the Klamath River the gravity high is flanked by two linear lows. One low is located along the southwest edge of Round Lake and the axis of the other low passes through Wocus Marsh. These two lows are believed to reflect structurally low areas. The greater amplitude of the low over Wocus Marsh suggests that it contains the greater thickness of low-density material.

The axis of a northwest-trending low passes through Round Lake. It may relate to the linear gravity anomalies in this area but the relationship is not clear.

A gravity and magnetic low are coincident with the northern part of Lower Klamath Lake, suggesting a deep structural depression filled with low-density material. A two-dimensional model (fig. A1) was prepared along gravity profile A-A'. The model assumes a density contrast of 0.4 g/cm^3 between the lower-density valley-fill and the enclosing bedrock and indicates about 2,000 m of fill.

Part of a gravity anomaly with 20 mgal or more of negative relief is located in the southwestern corner of the study area. The anomaly may reflect the roots of a basalt eruptive center as shown by Peterson and McIntyre (1970). They also show a mass of such rock 6 km to the east; however, the gravity data do not suggest an eruptive center underlying this area.

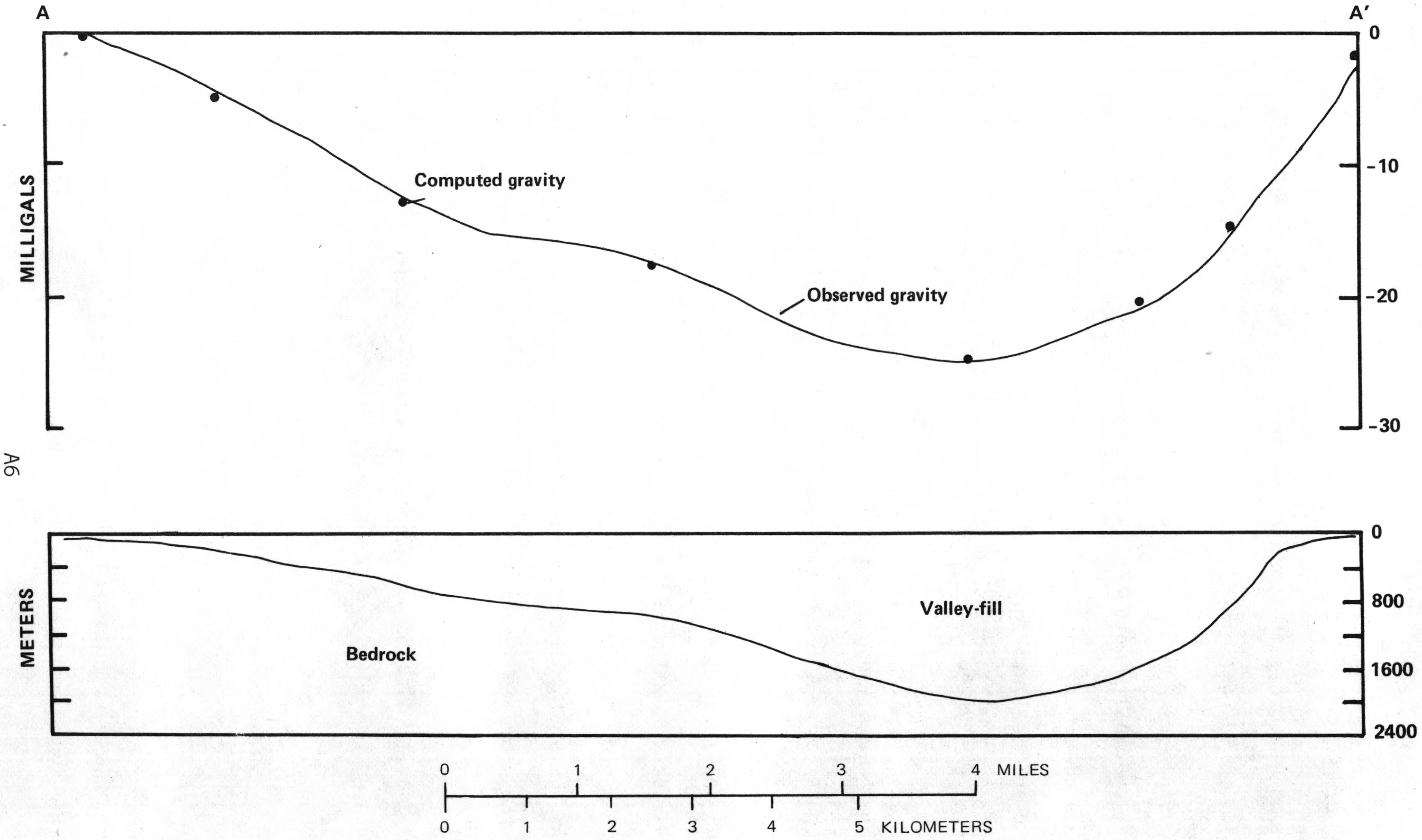

Figure A1. -- Two-dimensional model computed along gravity profile A - A'. Line of profile is shown in figure 17. No regional gravity gradient was removed from profile. A single density contrast of 0.4 grams per centimeter cubed was assumed.

The gravity field is poorly defined over much of Upper Klamath Lake. Steep gradients along part of the eastern edge of the lake are interpreted to reflect faulting. A gravity low, which terminates near Klamath Falls, is indicated over the lake; however, the gravity field over the lake might differ substantially if more data were available.

A northwest-trending gravity high coincides with Miller Hill. The data indicated that the hill continues southeasterly in the subsurface for another 2-3 km and northwesterly to the Klamath River. Miller Hill is not clearly reflected in the magnetic data. The steep gravity gradient bounding the northeast edge of the hill is interpreted to reflect a fault zone. Manning Ridge, which lies about 4 km southeast of Miller Hill, is not reflected in the data . Northwest of the Klamath River the magnetic and gravity patterns as relating to the Miller Hill, are not clearly defined.

An east-plunging gravity nose, about 5 km in length, is located just north of Kingsley Field and suggests a buried bedrock ridge. The steep gradients bounding the south and north edges of the nose suggest faulting.

A closed gravity high, bounded by steep gradients along its southeast and southwest edges, is located over Klamath Falls. The source of the gravity high is not known, but it does indicate that valley-fill in the area of the anomaly is thin.

Southeast of Klamath Falls, a closed gravity low is located over Altamont and vicinity. The low approximately coincides with the closed magnetic high which was inferred earlier to possibly relate to a buried igneous body. If the gravity low does indeed reflect an igneous body, then the body must consist of a low-density rock.

Several closed, gravity lows are located over the alluvium-covered lowlands. The more prominent of these lows are located east of Kingsley Field, a linear low over Miller Island and Spring Lake Valley, and another low northwest of Merrill. The low northwest of Merrill is probably structurally related to the low over Miller Island and Spring Lake Valley, being separated by a gravity saddle. These lows are intepreted to reflect the thickest sections of low-density material. The steep gradients bounding the northeast and, in part, the southwest edge of the gravity low near Merrill are believed to reflect northwest-trending fault zones. Other fault zones may be present; however, the data in many areas may be too sparse to reflect faulting.

A model (fig. A2) was constructed along gravity profile B-B' for the low east of Kingsley Field, and indicates 1,000 m of low-density material. A density constrast of 0.4 g/cm^3 was assumed between the low-density material and the enclosing bedrock. The thickness of low-density material indicated by the model is only an approximation because the anomaly is poorly suited for two-dimensional analysis.

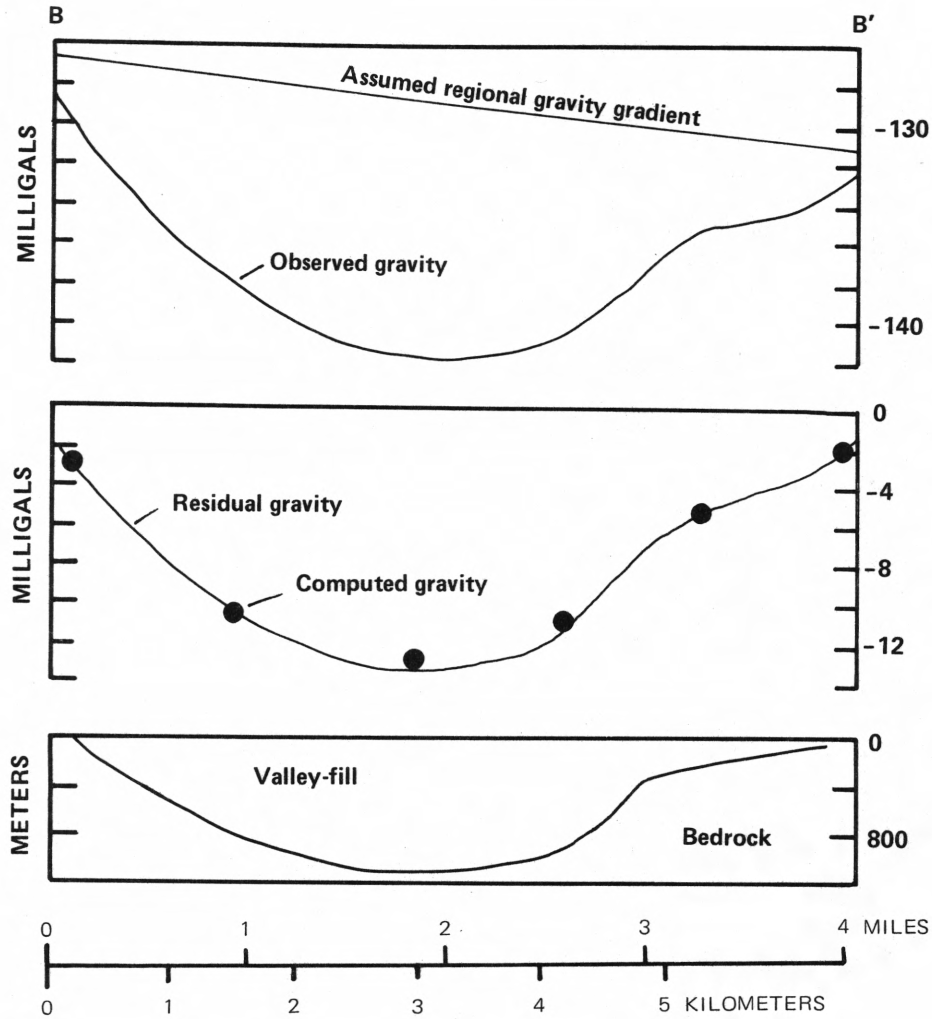

Figure A2. -- Two-dimensional model computed along gravity profile B - B'. Line of profile is shown in figure 17. A single density contrast of 0.4 grams per centimeter cubed was assumed.

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